Development of a Condition Based Maintenance Model for a Vessel's Main Propulsion Engine

By

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Abstract

Due to ever increasing demand of maritime transportation in the commercial shipping world vessel sizes are getting bigger and bigger. Generally, the type of the vessels are large bulk carriers, crude oil tankers, liquefied natural gas (LNG) carriers and mega container vessels, that are used to fulfil the demand of cargo transportation. Majority of these vessels are propelled by large slow speed main propulsion engines, directly coupled to the propeller, hence the on-board propulsion system plays a key role in maritime transportation. However, Australian Transport Safety Bureau (ATSB), Marine Accident Investigation Bureau (MAIB), U.K, Japan Transport Safety Board, National Transport Safety Board, U.S.A, identified that numerous accidents happened in the past due to the failure of main propulsion engine. The failure of main propulsion engine may lead to disastrous consequences, resulting in huge financial losses and crew fatality on ships. Therefore, it is required to ensure the safety and reliability of the main propulsion engine to ensure safe and reliable maritime transportation. This can be can be ensured by adopting an efficient and effective maintenance regime

Currently, the main propulsion engines on ships have a Planned Maintenance System (PMS), as required by the International Safety Management (ISM) code, under the directive of the International Maritime Organisation (IMO). In PMS system, the maintenance is carried out on ship's machinery based on regular intervals, according to engine and component manufacturer's advice and experience of ship's Chief Engineer and/or Master. However, studies from literature review undertaken, shows that the PMS is not the best form of maintenance regime. Literature reveals the fact that sister transport industries like railways, aircraft industry, and other process industries like chemical and oil and gas, use operational components similar to those used on ships. Such industries have adopted a Condition Based Maintenance regime (CBM), where maintenance of the system components is carried out based on the condition of the equipment, which is detected by measuring various useful parameters during the operation of the engine. All sister transport industries have reaped huge benefits by employing CBM in terms of maintenance cost and at the same time ensuring high levels of reliability Hence, employing CBM on ships could result in avoidance of wasteful resources in terms of manpower, spare parts and money. Shipping industry is lagging far behind in terms of employing CBM. This has been the foundation and motivation of this study to develop a CBM model for a vessel's main propulsion engine. The main propulsion engine is dependent on several sub systems to perform a safe and reliable voyage. In this study,

CBM model for the main propulsion system is developed. This model first evaluates the reliability of each subsystem and followed by evaluation of reliability of the main propulsion engine. The novelty of the CBM model developed for the vessel's Main Propulsion Engine is Reliability Centred Maintenance (RCM) model, which will assist to reduce the maintenance cost.

This thesis consists of seven chapters. The first chapter is an Introduction, highlighting the general structure of the thesis. In Chapter 2, the authors have put efforts to evaluate the development of large slow speed engines over the past four decades and the changes in system design which besides improving technical efficiency and contribution to combat the environment pollution, also looked at the economic factors and how this could be correlated to reliability of the main propulsion engine. The results conclude, development of turbochargers will play a major role in complementing and improving the overall efficiency and reliability of the main propulsion engine. The details of development of a CBM model for vessels' main propulsion system and related subsystems is presented in Chapter 3. This chapter also highlighted various tools used in the determination of reliability for the main engine subsystems. The results of this chapter identified that only following a PMS regime on-board vessel could lead to a machinery failure, resulting in stoppage of a vessel at critical juncture. Thus, changing from PMS to CBM is justified in merchant shipping. Fault Tree Analysis and Reliability block diagrams are utilised as important tools in this thesis. The Chapter 4 considered the basic steps involved in determining the reliability of the lubricating oil system, which is one of the subsystem of main engine. This chapter also includes methods of determining the reliability of main engine's fuel oil system and its impact on the reliability of the main propulsion engine. The results of this chapter demonstrates that use of additional components in the lubricating oil system could provide improvement in the component reliability leading to improved reliability of the main propulsion engine. To determine the cost benefit for using the additional component in the lubricating oil system, the incremntal reliability for the differential cost should be compared with the base relaibility to cost ratio. Utilizing the least failure rate of the fuel oil system component, as an identical value of failure rate for all components in the fuel oil system, the overall reliability of the main engine fuel oil system could be improved considerably. In Chapter 5 the authors developed a hybrid model to determine reliability of the main engine using Markov modelling and Weibull distribution. This chapter also considered a holistic approach to reliability and safety of a main propulsion engine in a harsh working environment. In

Chapter 6 the authors studied data gathered from experienced sea going marine engineers and analysed. The final chapter provides overall conclusions of this study along with some recommendation and direction for future research.

Keywords:
Main propulsion engine, Reliability assessment, Maintenance operation, Condition Based Maintenance, Reliability Centred Maintenance, Surveying, Data collection

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Declaration and Statements

Declaration of Originality

I declare that this is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been duly acknowledged in the text and a list of references is given.

Signature: Date: 14/11/2018

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Statement of Ethical Conduct

To develop the methodologies and tools data collection from the seafarers around the globe was required in this PhD research. Therefore, a human research ethics approval was obtained from the University of Tasmania's human research ethics committee (Ethics Ref No: H0014474).

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Dedication

This thesis is dedicated to my beloved parents **Late Mr. N.P. Anantharaman and Late Mrs. Maragatham Anantharaman, my father in law Late Prof. Janardhanan and mother in law Smt. Sarada and all my teachers**

"Who blessed me with their knowledge and invaluable support at all times".

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List of Abbreviations

ABS	American Bureau of Survey
ATSB	Australian Transport Safety Bureau
BN	Base Number
BP	Booster Pump
CBM	Condition Based Maintenance
CFD	Computational Fluid Dynamics
CLR	Cooler
CPR	Controlled Pressure Relief
DOD	Department of Defence
EEDI	Energy Efficiency Design Index
EGE	Exhaust Gas Economiser
FEM	Finite Element Method
FL	Filter
FM	Flowmeter
FOS	Fuel Oil System
FS	Fuel Oil Supply Pump
FTA	Fault Tree Analysis
GHG	Green House Gas
HT	Steam Heater
IMAREST	Institute of Marine Engineering, Science and Technology
IMO	International Maritime Organisation
ISM	International Safety Management
LNG	Liquefied Natural Gas

MAIB	Marine Acccident Investigation Bureau
ME	Main Engine
MEP	Mean Effective Pressure
MTBF	Mean Time Between Failures
NECA	NOx Emission Control Areas
NOx	Oxides of Nitrogen
Pmax	Peak Pressure
PMS	Planned Maintenance System
QC	Quick Closing Valve
RBD	Reliability Block Diagram
RBM	Risk Based Maintenance
S	Strainer
SCR	Selective Catalytic Reactor
SECA	SOx Emission Control Areas
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SIPWA	Sulzer Integrated Piston Ring Wear Arrangement
SOLAS	Safety of Life at Sea
SOx	Oxides of Sulphur
TBO	Time Between Overhauls
TCV	Temperature Control Valve
VIS	Viscotherm
VLCC	Very Large Crude Carrier
VTI	Variable Turbine Inlet

1. Introduction

1.1 Background

The main propulsion engine is the heart of any vessel sailing on high seas. It is an absolute requirement that the vessel transports its passengers, crew and cargo safely from one port to another. This can be accomplished if the main engine propelling the ship is reliable. The design and manufacturing of the main engine is within the domain of the engine builder, and is carried out taking into consideration the rules set by the Classification societies Eyres and Bruce (2012) and safety requirements of the International Maritime Organisation (IMO), (Mankabady, 1987). The IMO specifies the rules and engine manufacturers take proactive steps in designing the engine and constructing the engine, taking into consideration the 3E's which are efficiency, economy and environment protection (McIlgorm et al., 2011; Psaraftis and Kontovas, 2010). Availability of superior quality material for manufacturing engine components, superior computer aided tools, such as Computational Fluid Dynamics (CFD), and Finite Element Methods (FEM)) for design, have gone a very long way to make efficient marine engines (Fonte et al., 2015; Lamas and Rodríguez Vidal, 2012).These changes have also effectively addressed the stringent environmental protection requirements set by the IMO. These engines have also given the shipping industry higher engine power to ship's dead weight tonne (dwt) ratio, which provides higher cargo carrying capacities for ships, an advantage to the ship owners, and which addresses the second 'E' (economy factor). However, gruelling fuel oil prices form a large proportion of the running cost (Lindstad et al. (2013), and fierce competition between shippers to provide lower freight charges, require ship owners to keep the running costs as low as practicable. The main propulsion engines have to be highly reliable and safe at all times, which can be ensured by adopting an efficient and effective maintenance regime (Dikis et al., 2015). Currently shipping companies employ a practice of planned maintenance system (PMS) where maintenance is carried out based on regular intervals provided by the engine manufacturers. As stated by Anderson (2015), The International Safety Management (ISM) code, added as a chapter to the Safety of Life at Sea (SOLAS) Convention of the IMO addressed PMS. The ISM code was implemented in 2002. Generally, ship management companies consider the vast sailing experience of ship's Chief Engineers or Masters, while designing the PMS (MacDonald, 2006). However, studies from literature show PMS is not the best form of maintenance regime. Literature reveals the fact that sister transport industries (i.e. railways and aircraft industries), and other process industries (i.e. chemical and oil and gas) use operational components similar to those used on ships. Such industries have adopted a Condition Based Maintenance (CBM) regime (Bengtsson 2004), where maintenance of the system components is carried out based on the condition of the equipment. The condition of the equipment is identified by measuring various useful parameters during the operation of the engine. The aforementioned, sister transport industries have reaped huge benefits by employing CBM in terms of savings in maintenance cost and ensuring high levels of reliability (Bayoumi et al., 2008; Fumeo et al., 2015; Lagnebäck, 2007; Prajapati et al., 2012). However, the shipping industry is still lagging far behind in terms of employing CBM (Alhouli, 2011). Therefore, the motivation of this research is to develop CBM for the main engine of a ship. The developed methodology of this research will help to minimize the maintenance cost and increase the reliability of the main engine.

1.2 Research objectives and questions

The aim of this PhD thesis is to develop a methodology and tools to assess reliability and condition-based maintenance (CBM) of a main propulsion engine used in large commercial vessels at sea. This aim is achieved through the following objectives:

- To develop detailed understanding of the main propulsion engine and identify critical components and subsystems of the main propulsion engine;
- To develop an advanced reliability model for subsystems of the main propulsion engine;
- To collect and analyse real time data from ships, to test and verify the developed reliability model
- To extend the developed reliability model considering the harsh working environment of the main propulsion engine and;
- To develop CBM model for a ship's main propulsion engine;

To achieve the above objectives, it is necessary to riposte the following research questions:

- How to develop CBM for safe and reliable operation of a main propulsion engine?
- How to enhance reliability and safety of the main propulsion engine considering recent technical developments and IMO regulations?

- What are the tools required to evaluate reliability and enhance safety of the main propulsion engine?
- How to systematically evaluate the reliability of the main propulsion engine?
- How to assess the reliability of the main propulsion engine in a harsh working environment at sea?
- How to develop novel methods to analyse reliability of a main engine considering real time data from ships?

1.3 Scope and limitations

The primary aim of this thesis is to develop a methodology and tools to evaluate and quantify reliability of the main propulsion engine. As mentioned in the background section 1.1, the maritime transport industry is lagging behind its sister transport industries (Lazakis et al., 2010). It is vital to be guided by the methodologies employed in the sister transport industries, while developing the CBM model for the maritime industry.

The main propulsion engine depends on several subsystems for its operation. Each subsystem is analysed, utilising tools developed in the research, to evaluate and quantify reliability of the subsystem. This is followed by evaluation of the reliability of the main propulsion engine. On board large commercial vessels, the main propulsion engine forms the heart of the vessel and propels the vessel safely at high seas. Besides the main engine there are other machineries which make up for reliable and safe navigation and cargo handling on these vessels (Babel and Zimmermann, 2015, Ha et al., 2017). There are other important systems on board vessel which address comfort and health of the seafarers, including the refrigeration and air conditioning system. Based on the maritime labour convention MC 2006, it is a requirement to provide a minimum level of comfort to seafarers on board ships (Akyuz et al., 2015). The methodology and tools developed in this study for main propulsion engine will also be capable of evaluating the reliability of other systems (i.e. navigation, cargo handling equipment, refrigeration and air conditioning systems).

Data gathered from experienced engineers on board the vessels is utilised to perform the data analysis and to arrive at the final model. The methodologies adopted in this thesis can be compared with the incremental reliability to incremental cost ratio against the original reliability to the original cost. This would help the Master or Chief Engineer on board the vessel, and the shipping companies, in their decision-making process, when weighing reliability in terms of cost. An improved reliability for the incremental cost may prove to be highly desirable for certain piece of equipment/s of a subsystem but may not prove to be sustainable for some other equipment/s of the subsystem. The thesis also has the scope to give an insight into the safety and reliability of a main propulsion engine subjected to a harsh working environment. When the vessel encounters rough weather, reliability and safety must then be viewed from a different perspective. In a harsh working environment, the criticality of some specific component of the subsystem becomes more important than some other components of the sub system. A reliability compensating factor was defined and established and utilised in the thesis to evaluate the reliability of the main propulsion engine that is subjected to a harsh working environment (Anantharaman et al., 2017, Abaei et al., 2017).

Whilst the thesis has focussed on a large two stroke man propulsion engine, which propels large capacity vessels, it has limitations whilst dealing with smaller capacity vessels propelled by medium speed four stroke diesel engine (Sarvi et al., 2008). Although the subsystems of the main engine propelling smaller capacity vessels will be identical to the subsystems considered in this thesis, one need to consider other pieces of vital equipment which forms a critical part of the smaller vessels propelled by four stroke engines. One such component which is beyond the scope of this thesis is the reduction gear box, which will be very important piece of equipment for analysis.

Moreover, the data collected for the thesis gathered from experienced engineers serving on merchant vessels ranging in size from handy size bulkers to large VLCC's (very large crude carrier). The mean time between failures (MTBF) for various components of the main propulsion engines subsystems was taken as the main factor in reliability calculations.

1.4 Organisation of the thesis

The thesis is presented in a manuscript format (paper based). It consists of seven chapters, which are independent work. They are, however, connected to serve as an integrated comprehensive document for reliability assessment and CBM of the main propulsion system.

Each of the chapter consists of one or more scholarly published journal article or conference proceedings.

In Chapter 1, background information of the thesis has been highlighted, stating the research objectives, and the research questions. Moreover, the scope and limitations of the thesis are discussed and finally the organisation of the research is mentioned.

In Chapter 2, the authors have put efforts in evaluating the development of large slow speed engines over the past four decades and the changes in system design, whilst also improving technical efficiency and contributing to combatting the environment pollution. Moreover, the authors looked at the economic factors and how they could be correlated to reliability of the main propulsion engine. Commercial shipping industry employs many bulk carriers, crude oil tankers, LNG (liquefied natural gas) vessels and mega container vessels. These huge vessels require great magnitude of power to propel them at high seas. More than 85% of these vessels are propelled by large slow speed engines, directly coupled to the propeller. The past decade has seen considerable development in these large slow speed engines in terms of design, operational safety, and maintenance and fuel efficiency. Major engine builders have strived to achieve a higher level of efficiency of these engines. From the shipowner’s point of view, commercial shipping has become highly competitive and there is a dire need to reduce operation and maintenance costs to survive under the present market condition. Hence the economical aspect of running ships which is a very crucial commercial factor. The maritime regulators led by IMO ensure that the marine environment is clean and free from pollutants, which in this case would be the controlling of various pollutants discharged from the exhaust funnel of these large marine diesel engines. This chapter provides a comprehensive review of the various stages of development of large marine slow speed engines over the past four decades, and the factors that have influenced these developments. However, in the present-day context and in the near future there is the need to closely look at the commercial aspect of merchant shipping, and specifically address the three big ‘E’, for the maritime engineering world. The results of this chapter concluded that, more efficient turbocharging will play a major role in complementing and improving the overall efficiency and reliability of the main propulsion engine.

The details and development procedure of a CBM model for a vessels main propulsion system and related subsystems are presented in Chapter 3. This chapter also highlights various tools used in the determination of reliability for the main engine subsystems. The author emphasises the need to move from PMS to CBM in merchant shipping to reduce non-resourceful shipboard maintenance and achieve cost benefit. The shipping market is highly competitive, which coupled with high crewing and fuel costs leads to high operational costs. One of the paramount factor involved in vessel operation is maintenance cost and there is a dire need to keep this cost to a minimum level. This chapter introduces the usage of reliability engineering tools like Fault Tree Analysis (FTA) and Reliability Block Diagrams (RBD) and how they can be effectively employed to determine the reliability of the main engine subsystems and ultimately determine the reliability of the main Propulsion Engine. The results of this chapter identify that only following a PMS regime on-board vessel could lead to a machinery failure, resulting in stoppage of a vessel at critical juncture. Thus, moving from PMS to CBM is justified in merchant shipping.

The Chapter 4 considers the basic steps involved in determining the reliability of the lubricating oil system, which is one of the sub-systems of the main engine. This chapter also includes methods of determining the reliability of the main engine's fuel oil system and its impact on the reliability of the main propulsion engine. This chapter further discusses the methodology adopted to quantify reliability of the lube oil system and development of a model based on Markov method. Having developed the model, means to improve reliability of the system should be considered. The cost of the incremental reliability should be measured to evaluate cost benefits. A maintenance plan can then be devised to achieve the higher level of reliability. A similar approach could be considered to evaluate the reliability of all other sub-systems. This will finally lead to development of a model to evaluate and improve the reliability of the main propulsion system. The results of this chapter demonstrate that, the use of additional components in the lubricating oil system could provide improvement in the component reliability leading to improved reliability of the main propulsion engine. To determine the cost benefit for using the additional component in the lubricating oil system, the incremntal reliability for the differential cost should be compared with the base reliability to cost ratio. Utilizing the least failure rate of the fuel oil system component, as an identical value of failure rate for all components in the fuel oil system, the overall reliability of the main engine fuel oil system could be improved considerably.

Chapter 5 provides reliability assessment of vessel's' main engine by combining Markov analysis with time dependent failure. Safe operation of a merchant vessel is dependent on the reliability of the vessel's main propulsion engine. Overall reliability of the main propulsion engine is interdependent on the reliability of several subsystems including the lubricating oil system, fuel oil system, cooling water system and scavenge air system. The reliability of various components of certain system such as gear pumps in a fuel oil system or filters in a lubricating oil system, which exhibit constant failure rate (random failure) independent of their history of operation, could therefore be analysed using Markov modelling. Other vital component such as turbochargers exhibits time dependent failure rate (wearing out). The wearing out failure rate (increasing failure rates) can be analysed using Weibull distribution. This chapter presents integration of Markov model (for constant failure components) and Weibull failure model (for wearing out components) to estimate the reliability of the main propulsion engine. This integrated model will provide more realistic and practical analysis. It will serve as a useful tool to estimate the reliability of the vessel's main propulsion engine and make efficient and effective maintenance decisions. Moreover, this chapter represents the reliability assessment under harsh environment conditions. Sometimes the main propulsion engine of a vessel must operate under harsh environmental conditions i.e. very rough weather, concurrent failure of one or more units and failure of one or more sub-systems of the main engine. Such failures at high seas could lead to disastrous consequences, which could include damage to ship's machinery, injury and fatality of shipboard personnel and pollution of the sea. Reliability and safety of the main propulsion engine needs to be looked at holistically when the main engine operates under harsh environmental condition. Mathematical modelling for computing reliability of the main propulsion engine, combined with a relevant safety check list for the engine room, based on expert elicitation could be a good solution for an unremarkable voyage of the vessel under a harsh scenario. This chapter intends to look at the harsh scenario for a bulk carrier propelled by a large main propulsion engine and arrive at a plan for a safe and reliable voyage of the vessel.

Chapter 6 discusses the data collection procedure and analysis for the reliability assessment of the marine engines.

The final chapter summarizes the major findings of this PhD research and points out several new directions for future research.

1.5 Contribution by authors

This thesis comprises seven chapters, which are intertwined to serve as an integrated comprehensive document for reliability assessment and CBM of main propulsion system. Each paper is a scholarly work published as a journal article and conference proceedings co-authored by supervisory team. The below statement reflects the true role and contribution of co-authors in the paper.

This is to confirm that Mohan Anantharaman is the primary author of all the papers presented in this thesis. Along with co-authors, Faisal Khan, Vikram Garaniya and Barrie Lewarn, Mr. Anantharaman developed the conceptual model and subsequently translated this to the numerical model. I conducted the literature review and, collected relevant data. Coauthor Faisal Khan, assisted in developing and testing the reliability models, results interpretation and developing Condition Based Maintenance plan. Co-author Vikram Garaniya cross checked the models, its results, CBM plan and helped preparing the first draft. Co-author Barrie Lewarn shared his experience related to practical relevance and applicability of model and CBM method. Mr Anantharaman prepared the first draft of the manuscript and subsequently revised the manuscript based on the co-authors' feedback and also the feedback from the journal reviewers. All coauthors have helped in reviewing and revising the manuscript.

1.6 Problem statement

Currently in merchant shipping the maintenance practice widely employed is the "Planned Maintenance Regime", where maintenance of the engine component is carried out at intervals specified by the engine manufacturers or classification societies in accordance with the International Safety Management code (ISM), prescribed by IMO (International Maritime Organisation). Carrying out maintenance in this fashion, irrespective of consideration for the health of the machinery leads to wasteful use of resources in terms of manpower and cost. This may also introduce faults due to errors in maintenance, leading to breakdown of machinery and accidents.

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3. Develop a Condition Based Maintenance Model for Main Propulsion Engine

Abstract

Merchant shipping has undergone a great transformation over the past three decades. The shipping market is highly competitive, which coupled with high crewing and fuel costs, leads to high operational costs. One of the paramount factors involved in vessel operation is the maintenance cost and there is a dire need to keep this cost to a minimum. Fortunately, the earlier policy of repair only maintenance in commercial shipping has been done away with and replaced by the policy of preventive maintenance. Planned Maintenance System was introduced by ship management companies in the early 90s. Planned Maintenance offered benefits over the repair only policy but has its own shortcomings. Frequently machinery equipment is opened for routine maintenance after a specified time interval, irrespective of the need. This could lead to potential failures explained by the fact that preventive maintenance resulted in meddling with a well-set piece of machinery equipment, leading to its subsequent failure. This is where Condition Based Maintenance or CBM steps into prominence. CBM monitors the health of the machinery equipment, analyses the condition and helps in decision making. The Main Propulsion system forms the heart of a vessel and we need to ensure its reliability, together with the reliability of its associated subsystems. The entire system can be represented by reliability block diagrams, to show the interdependence of various components comprising the system. This helps in the decision-making process of CBM whereby the ship's engineer may decide to stop the running machinery equipment, open and overhaul the same.

3.1 Introduction to Planned Maintenance System

Commercial shipping in the modern world is highly competitive, which coupled with high crewing and fuel costs, leads to high operational costs. One of the paramount factors involved in vessel operation is the maintenance cost and there is a dire need to keep this cost to a minimum. Fortunately, the earlier policy of repair only maintenance in commercial shipping has been done away with and replaced by the policy of preventive maintenance. Planned Maintenance System was introduced by ship management companies in the early 90s.

3.2 Why Condition based maintenance?

Planned Maintenance offers benefits over the repair only policy but has its own shortcomings. Often machinery equipment is opened for routine maintenance after a specified time interval, irrespective of the need. This could lead to potential failures, explained by the fact that preventive maintenance resulted in meddling with a well set piece of machinery equipment, leading to its subsequent failure (Bhattacharya, 2012). The author cites an incident experienced during his extensive sailing career. A general cargo vessel was on her way from India to Europe. This passage involves the Suez Canal transit where large numbers of vessels transit in convoy. A few days prior to transiting the Suez Canal the No.1 Steering gear motor was opened for routine overhaul, as specified in the Planned Maintenance Schedule for the vessel. The motor was overhauled and reassembled. The vessel then entered the convoy and all went well for an hour under the guidance of the Suez Canal pilot who travels on board the ship during the transit. The pilot then ordered a helm movement and the vessel failed to steer as required. The reason was overload tripping of the overhauled motor, and investigations revealed errors made during the reassembly of the motor. The vessel then tied alongside the canal with the help of tugs, the motor had to be reopened, and new bearings fitted. The motor was tested and finally the vessel managed to transit the Suez Canal, although she had to be last in the convoy resulting in considerable losses to the company in terms of thousands of dollars. This is where Condition Based Maintenance or CBM becomes important. CBM monitors the health of the machinery equipment, analyses the condition and helps in decision making. Accordingly, a ship's engineer may decide to stop the running machinery equipment, open and overhaul the same, or else postpone the overhaul for a later, safer date.

3.3 ISM Code and Maintenance

When it comes to operation of ships, all shipping companies need to abide by the ISM Code which is the International Safety Management Code**,** the purpose of which is to provide an international standard for the safe management and operation of ships and for pollution prevention. The above research will also address section 10.3 of the code which states that, "The Company should identify equipment and technical systems the sudden operational failure of which may result in hazardous situations". The safety management system should provide for specific measures aimed at promoting the reliability of such equipment or systems. These measures should include the regular testing of stand-by arrangements and equipment or technical systems that are not in continuous use (Rodriguez and Hubbard, 1998)

3.4 Diagnosis and Prognosis

The concept of CBM for ships' machinery is still in its infancy. Reproducing a recent finding which says "However, according to class records, only about 2% of the world fleet is operating using CBM" (MER,2012). Effective application of CBM techniques will result in large savings to the vessel owner / operator. A ship's machinery space is a large main propulsion system with several subsystems. All these systems have a high degree of correlation and failure of any one subsystem could result in stoppage of the vessel, which is a highly undesirable event. CBM is a two-sided coin with diagnosis on one side and prognosis being the other side. For an efficient vessel operation both sides of the coin are vital. Prognosis is an important element of the CBM program as it deals with the prediction of failure faults. The above research should be useful to predict the occurrence and timing of a failure in a single subsystem (for example a ship's main propulsion and power generation system) or in several different subsystems (for example a ship's main propulsion and power generation system and control air system).

3.5 Gross Maintenance Deficiencies

A few instances of major shipping disasters resulting from gross maintenance deficiencies have been highlighted below. This information was gathered from leading reputable Marine Accident Investigation bodies in the commercial shipping world. The scavenge space inspection after the fire in number three unit, shortly after the first turbocharger failure, apparently revealed a high level of scavenge fouling. Similarly, the condition of the scavenge spaces after the second turbocharger failure was poor around number two cylinder, albeit because of piston cooling oil leaking from the defective O-ring. Whether or not the condition of the scavenges led to a fire, which in turn caused the turbocharger failures, cannot be concluded with any certainty however their condition does indicate that the vessel's main engine maintenance regime in this respect have been deficient (Australian Transport Safety Bureau, 2006).

Figure 3.1: Condition of scavenge ports on Cylinder no. 1 of Main Propulsion Engine Source based on ATSB (2006)

Figure 3.2: Condition of scavenge ports on Cylinder no. 2 of Main Propulsion Engine Source based on ATSB (2006)

Figure 3.3: Condition of main propulsion turbocharger rotor. Source based on ATSB (2006)

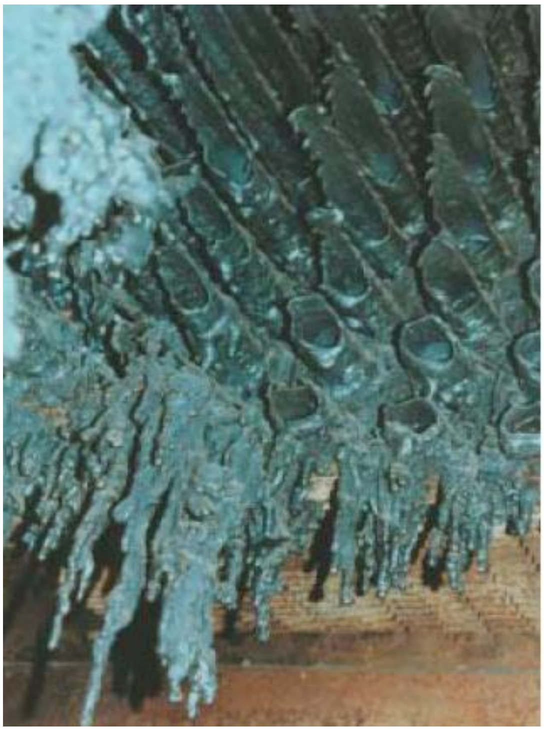


Figure 3.4: Condition of damaged exhaust gas boiler tubes. Source based on MAIB (2007)

Apart from the failure of the auxiliary boiler, there were other examples where equipment did not work appropriately that were attributable to ineffective maintenance or equipment checks:

- Standby EGE circulation pump mechanical seal
- Automatic operation of soot blowers
- Fuel tank quick closure valves
- CO2 drench pilot operating system
- Emergency diesel generator overheating
- Emergency fire pump suction

The maintenance system recorded that checks and planned maintenance were complete on all these items, and that there were no defects. While it is always possible for equipment to not work in an emergency, so many serious defects should not occur during the same incident. Neither the maintenance system nor any of the technical audits detected these latent defects, so the effectiveness of these systems must be questioned (MAIB, 2007).

CBM leads to improved reliability of the machinery equipment and better inventory control of spares on board the vessel. This approach to maintenance has been advised to ship owners by leading classification societies(Robert, 2004). By applying Reliability-Cantered Maintenance (RCM) principles, maintenance is evaluated and applied in a rational manner that provides the most value to a vessel's owner/operator. Accordingly, improved equipment and system reliability on board ships and other marine structures can be expected by applying this philosophy.

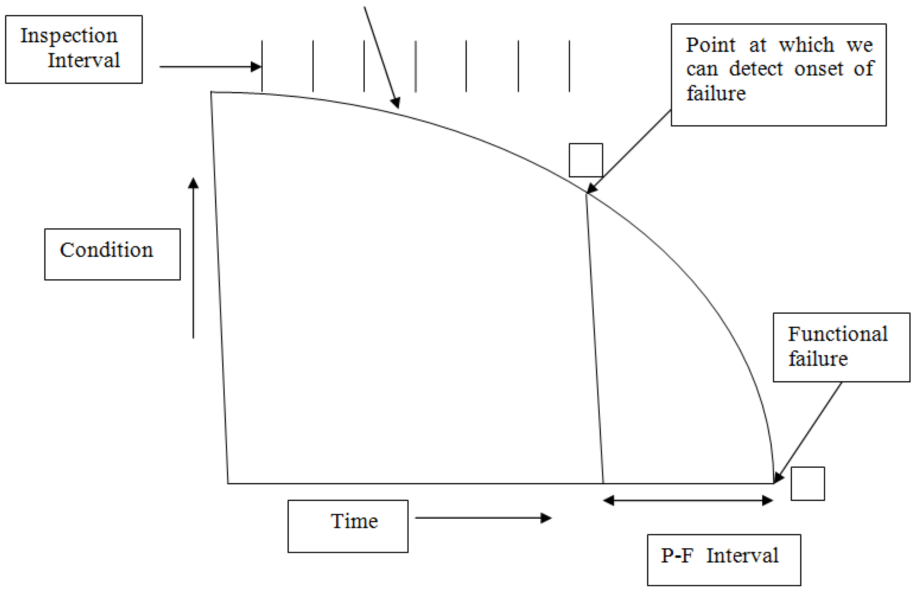


Figure 3.5: P- F Diagram Source ABS guidance notes 2004

ABS guidance notes on Reliability Cantered Maintenance- 2004 highlights the P-F interval. If a potential failure is detected between Point P and Point F, it may be possible to take action to prevent the functional failure (or at least to minimise its effects). Tasks designed to detect potential failure are known as condition-monitoring tasks. See Figure 3.5 above.

My research proposal is to focus on the main propulsion system and related subsystems (Figure 3.6) on commercial bulk carriers and naval vessels, collect data for these main and subsystems which will then be processed for statistical analysis and produce a reliable maintenance model for the vessel. To begin with, the research will be exploratory in nature, collecting data pertaining to real life examples and case studies published by (reputable) marine accident investigation bodies in world shipping as mentioned above. I shall then start building my theory developing from the knowledge gained in the exploratory process stage. This should eventually lead to development of a hypothesis which will be tested statistically for a large sample size.

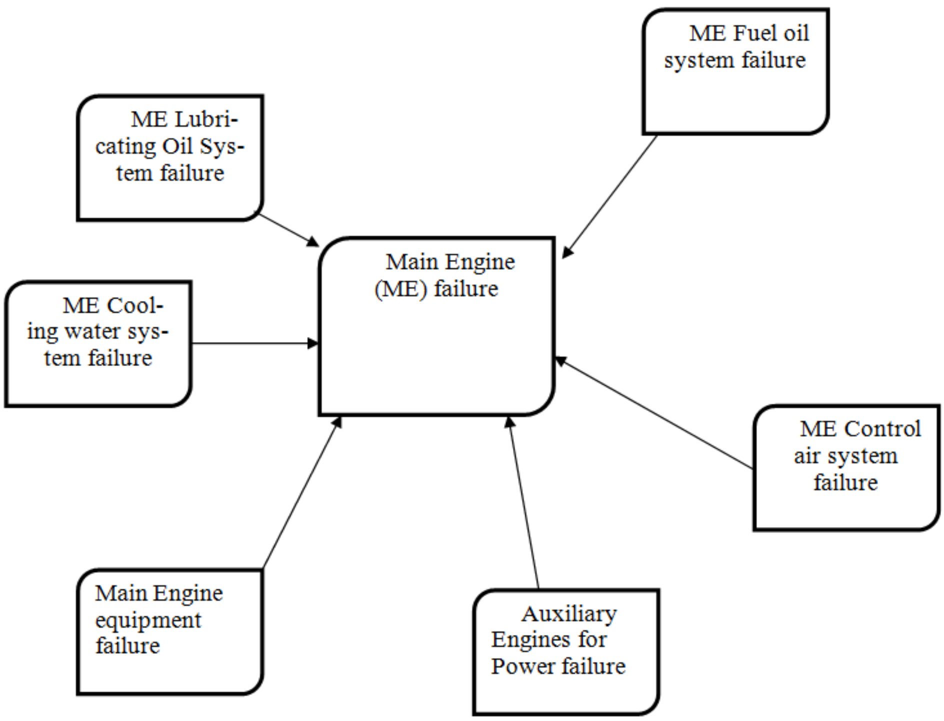


Figure 3.6: Main propulsion system and related subsystems for large vessels.

3.6 Fault Tree Analysis

It is intended to use FTA (Fault Tree Analysis) during development of the CBM (Condition Based Maintenance) model. FTA is a top down approach, which helps to identify basic events which can lead to the top undesirable event. I have included a few quotes from my earlier research work below. Looking at the fault tree, one can easily recognise that a basic event of a distillate pump failure by itself can cause the top undesirable event to occur. Furthermore, past sailing experience of the author provides sufficient cases of Fresh Water Generator failure because of failure of the distillate pump. Hence the emphasis should be to avoid this basic event(Anantharaman, 2002).

A bulk carrier is a vessel which carries cargo in bulk. Modern bulk carriers can load around 400,000 tons of iron ore, and can be hired at a rate of USD10 per ton, with a turnaround of less than 24 hours. Delay of vessels in ports could result in loss of a charter in addition to the additional port charges, pilotage and other associated expenses. In one case a fully loaded Panamax bulk carrier under ballast condition had arrived at a Port to load coal. (A Panamax bulker is a vessel, which transits the Panama Canal, restricted by the vessel's beam, maximum 32metres.) The vessel had a major problem pumping out her ballast before berthing. The bulk carrier had 10,000 tons of ballast water in the ballast hold. Blockage of a filter in the ballast pumping system of the cargo hold, led to a major problem of the vessel not being in a state of readiness to load cargo in port. This had huge financial implications on the ship's management organisation. Carrying out a FTA (Fault Tree Analysis), enables one to identify the root cause of the problem and corrective steps could then be taken to prevent a basic undesirable event from occurring, and thus avoid the major problem of disruption in loading of cargo(Anantharaman, 2003, Zhu, 2011). In this case the basic undesirable event happened to be a clogged strainer in the cargo hold, which called for a modification, costing a few hundred dollars and three (3) man-hours to the ship owner.

The fault tree circuit for the above case study is shown below in Figure 3.7, where a minor event, Y1, could lead to the top undesirable event.

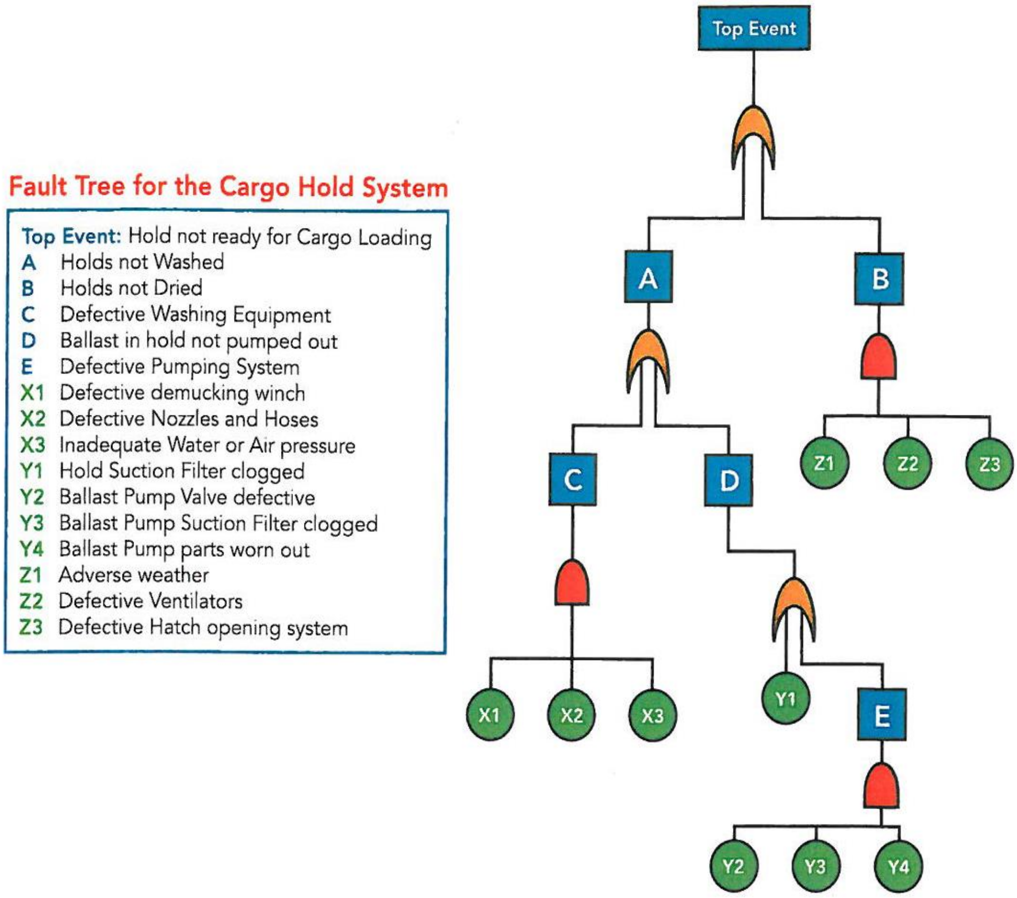


Figure 3.7: Fault Tree for a ship's Cargo Hold System

A case study was also done on a Fresh Water Generator plant. A fault tree analysis was carried out, which led to a conclusion that failure of a distillate pump in the plant could lead to the stoppage of a vessel at sea. In this study the vessel suffered financial losses owing to ineffective spare parts management (Hidalgo et al, 2011).

Basic Events for Ship's Fresh Water Generator Fault Tree

Refer: Figure 3.8 below

Y1	Ejector Pump Strainer blocked
Y2	Ejector pump piping / valve defective
Y3	Ejector Pump motor/coupling drive breakdown
Y4	Ejector Pump parts wear excessive
Y5	Alternate source of sea water from Fire & GS pump unavailable
Y6	Feed sea water not available for ejector
Y7	Heating water from Main Engine not available
Y8	Steam from Boiler not available to Heat Exchanger
X1	Cooling water not available to Heat Exchanger
X2	Clogged demister vapour inlet to condenser
Z	Breakdown of distillate pump
A	Sea water supply for Eductors and feed not available
B	Heat Exchanger breakdown
C	Condensor breakdown
D	No sea water supply to from Ejector pump
E	No heat input to Heat Exchanger

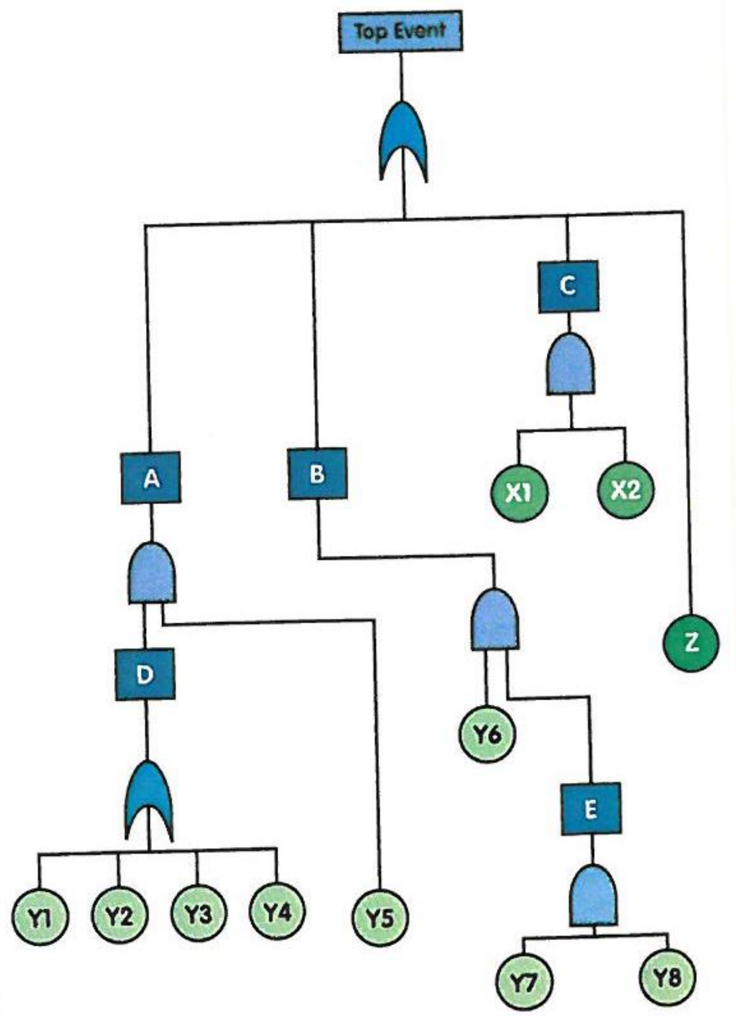


Figure 3.8: Fault tree for a ship's fresh water generator

3.7 Reliability Block Diagram (RBD)

Another useful methodology found to be useful is developing Reliability Block Diagrams (RBD) depicting the functional relationships between components comprising a system. Previous researches have shown that RBDs can be transformed to Bayesian networks (BNs) to represent probabilistic relationships between uncertain variables. Previous research has described how one can transform an RBD into a BN. A fault tree circuit can be constructed directly from an RBD and is more efficient than an arithmetic circuit that is compiled from the BN corresponding to that RBD. We developed several methods for fault tree circuits, highlighting how they can aid the analyst in efficient diagnosis, sensitivity analysis, and decision support for many typical reliability problems. The circuit framework can complement tools that are popular in the reliability analysis (Bhattacharjya and Deleris, 2012). Figure 3.9 below shows an RBD for a Lubricating oil system for a large Marine Diesel Engine.

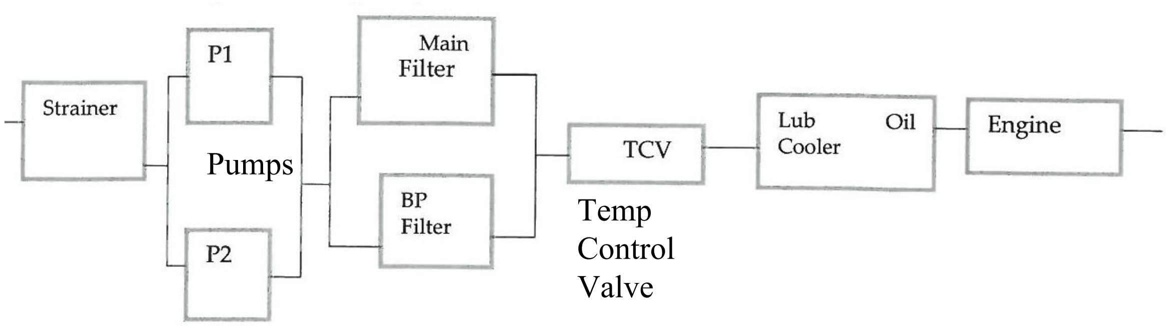


Figure 3.9: RBD for Main Engine Lubricating oil system

3.8 Conclusion

It is seen in this paper that at times, by just following a PMS regime on board vessels could lead to machinery failure, resulting in stoppage of a vessel at a critical juncture (Anantharaman and Lawrence, 2013). In mercahnt shipping it is very important to change from PMS (Planned Maintenance System) to CBM (Condition Based Maintenance). The main propulsion plant of a vessel should be the focal point of CBM and can work around the related susbsystems. Fault tree analysis (FTA) is one such approach wherein the basic event can be identified, the failure of which could lead to a possible catastrophic failure of the plant. The probability of failure of the system components using statistical tools for analysis needs to be looked into.

A neur-fuzzy modelling approach for CBM was effectively utilised by researchers in merchant shipping and other shore based industries (Kothamasu and Huang, 2007, Xu et al, 2010). This transformation could lead to huge benefits to cost ratio, at the same time ensuring safety and reliability.

4. Evaluating the reliability of the main engine lube and fuel oil systems

This chapter considered the basic steps involved in determining the reliability of the lubricating oil system, which is one of the subsystems of the main engine. This chapter also includes methods of determining the reliability of the main engine's fuel oil system and its impact on the reliability of the main propulsion engine.

Additionally, this chapter discusses the methodology adopted to quantify reliability of the lube oil system, and development of a model, based on Markov analysis. Having developed the model, means to improve reliability of the system should be considered. The cost of the incremental reliability should be measured to evaluate cost benefits. A maintenance plan can then be devised to achieve the higher level of reliability. A similar approach could be considered to evaluate the reliability of all other subsystems. This will finally lead to development of a model to evaluate and improve the reliability of the main propulsion system. The results of this chapter demonstrate that use of additional components in the lubricating oil system could provide improvement in the component reliability leading to improved reliability of the main propulsion engine. To determine the cost benefit for using the additional component in the lubricating oil system, the incremntal reliability for the differential cost should be compared with the base reliability to cost ratio.

Utilizing the least failure rate of the fuel oil system component, as an identical value of failure rate for all components in the fuel oil system, the overall reliability of the main engine fuel oil system could be improved considerably.

The research on the two subsystems of the main propulsion engine, viz. the lubricating oil system and the fuel oil system, were presented in the form of two peer reviewed publications and have been presented below:

4A A step by step approach for evaluating the Reliability of the Main Engine Lube Oil system for a ship's propulsion system.

4B Reliability of fuel oil system components versus main propulsion engine: An impact assessment study.

4A. A step by step approach for evaluating the Reliability of the Main Engine Lube Oil system for a ship's propulsion system.

Abstract

Effective and efficient maintenance is essential to ensure reliability of a ship's main propulsion system, which in turn is interdependent on the reliability of several associated subsystems. A primary step in evaluating the reliability of the ship's propulsion system will be to evaluate the reliability of each of the subsystems. This paper discusses the methodology adopted to quantify reliability of one of the vital subsystems viz. the lubricating oil system, and development of a model, based on Markov analysis. Having developed the model, means to improve reliability of the system should be considered. The cost of the incremental reliability should be measured to evaluate cost benefits. A maintenance plan can then be devised to achieve the higher level of reliability. A similar approach could be considered to evaluate the reliability of all other subsystems. This will finally lead to development of a model to evaluate and improve the reliability of the main propulsion system

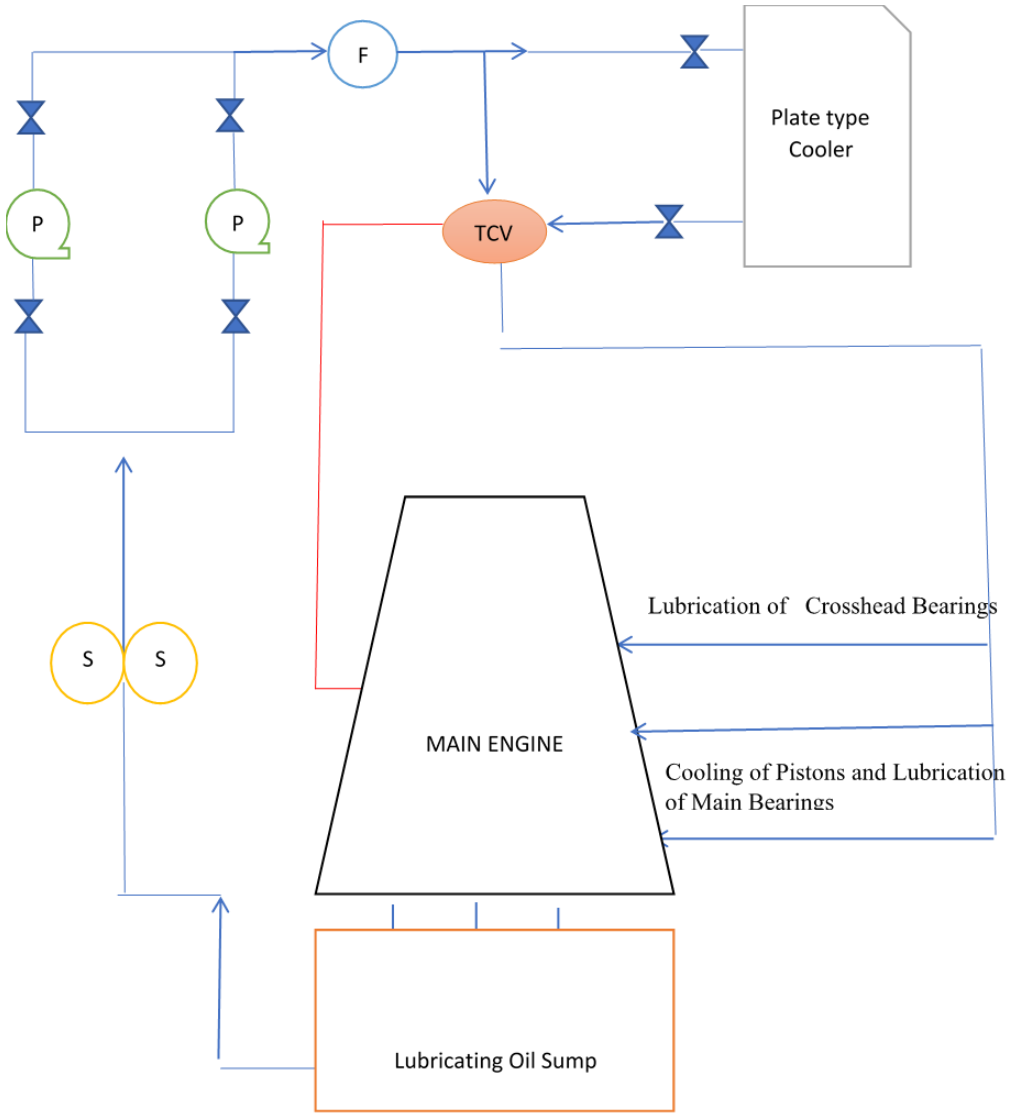
Keywords: Main Propulsion system, Lubrication Oil System, Condition Based Maintenance, Reliability, Markov analysis.

4A.1 Introduction

The main propulsion engines which propel the vessels at sea must always be highly reliable and safe, whilst sailing on the high sea, transiting through canals and manoeuvring in ports. It is imperative that the maintenance regime on board the vessels must be very well structured, with utmost consideration to safety and reliability of the main propulsion system. The reliability of the main propulsion system is interdependent on the reliability of its subsystems, which are listed below.

i. Main Engine Lubricating Oil system
ii. Main Engine Jacket Cooling Water system
iii. Main Engine Fuel Oil system
iv. Main Engine Scavenge system
v. Main Engine Air Start system
vi. Main Engine Safety System

This paper discusses the methodology adopted to quantify reliability of one of the vital sub-system viz. the lubricating oil system (Mollenhauer and Tschöke, 2010), and development of a model.



S	Suction Strainer
P	Pump
F	Discharge Filter
TCV	Temperature Control Valve
(red line)	Temperature Sensing Line

Figure 4A.1: Main Engine Lubricating oil system for a large two stroke engine

On large two stroke engines the lubricating oil sump capacity may be as high as 30,000 litres. The lube oil pump strainer is a wire mesh type located in the sump, from where the pumps draw the lube oil and deliver it through a fine mesh 25 microns discharge filter, to the main engine lube oil plate type highly efficient cooler, the medium of cooling being sea water. There is a Temperature Control Valve as shown in Figure 4A.1, which controls the lube oil flow through the cooler as per the required temperature to the engine inlet. Normally the lube oil inlet temperature to the engine will be 40 -42 degs C. The function of the lubricating oil is to lubricate the main bearings, cross-head bearings (the connecting rod top end) and the big end bearings (connecting rod bottom end). It also supplies oil to the piston crown and cools the crown to an acceptable working temperature in the engine. Failure of the Main Engine Lubricating Oil System could lead to major damage to engine components, resulting in expensive repair and replacement costs.

To evaluate the reliability of the lubricating oil system, a systematic approach involving a Fault Tree Analysis (FTA) for the system, will be considered. This will be followed by a Critical Component Identification (CCI) and then a Reliability Block Diagram shall be developed (RBD). A model to evaluate the reliability for each system component is developed and the overall reliability of the system can be determined.

The various components of the Main Engine Lubricating oil system will now be looked at (Cicek and Celik, 2013), and reliability of the system determined . The following steps are followed:

i. The Fault Tree Analysis (FTA) for the Main Engine Lube Oil system (Zhu, 2011)
ii. Develop a Reliability Block Diagram (RBD) for the Main Engine Lube Oil system(Bhattacharjya and Deleris, 2012)
iii. Look at the individual components in the Main Engine Lube Oil system and draw the state diagram for these components
iv. Carry out a Markov Analysis for these components (Gowid et al., 2014)
v. Carry out a relaibility analysis
vi. Consider measures for improving the system reliability
vii. Draw conclusions based on the analysis

4A.2 The FTA diagram for the Main Engine Lube Oil System

There are five (5) main components of the M.E. Lube Oil system, failure of any of which will lead to the failure of the main propulsion engine.

In Figure 4A.2, S represents the main engine lube oil pump strainer, P represents the pumps, F represents discharge filter, and TCV is the temperature control valve and CLR the main engine lube oil cooler.

The next step in the analysis of evaluating the Reliability of the Main engine Lube Oil sysytem is as shown below:

The following five (5) cases are analysed:

i. Failure of suction strainer S
ii. Failure of pumps P
iii. Failure of discharge filter F
iv. Failure of Temperature Control Valve TCV
v. Failure of cooler CLR

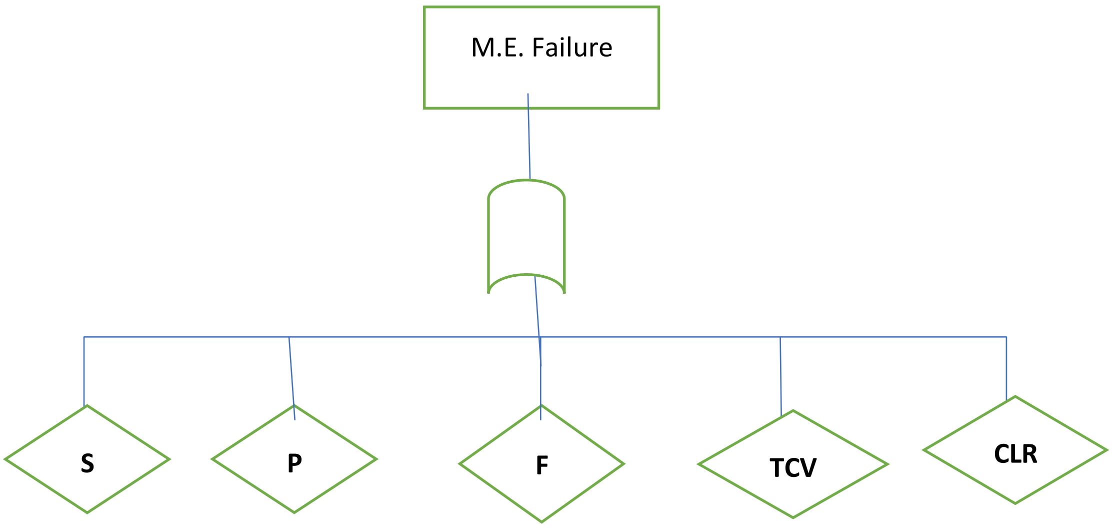


Figure 4A.2: Fault Tree diagram for M.E. Lube Oil system

4A.3 RBD for the Main Engine Lube Oil System

The following points are taken into consideration.

1. Each block represents the maximum number of components in order to simplify the diagram.
2. The function of each block is easily identified
3. Blocks are mutually independent in that failure of one should not affect the probability of failure of another (Anantharaman, 2013, Xu, 2008).

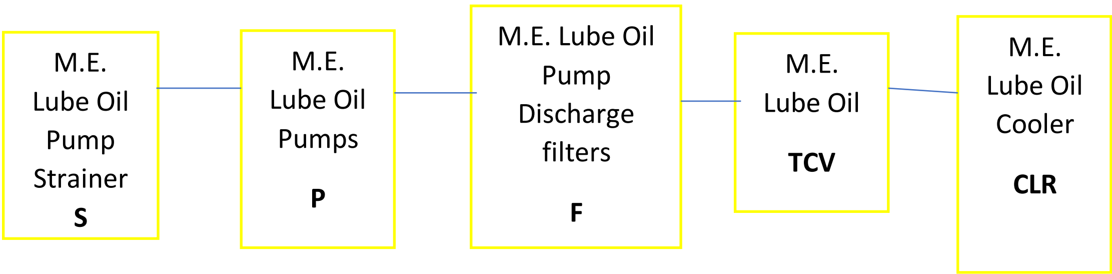


Figure 4A.3: Detailed RBD for M.E. Lube Oil system, with all system components

4A.4 State Diagram for the Main Engine Lube Oil Strainer (S)

The first component suction strainer S is a basket type strainer, located before the lubricating oil pumps (Khonsari and Booser, 2008). This is a duplex type of filter with a changeover cock for isolation of filters. One of the filters is in use, the second one being on standby. Clogging of the strainer can result in the pump's inability to draw suction from the sump, which may sound a low-pressure alarm. This allows time for changing over to the standby strainer. Failure of this standby will result in pump failure, finally resulting in an engine failure. These filters will be identical to those shown in Figure 4A.4 below. The state diagram for the filters is shown in Figure 4A.5 below. The reliability function is an exponential function of time t and the failure rate λ expressed as number of failures per running hours.

Figure 4A.4: Lube oil suction strainers for the Main Engine Lube oil system

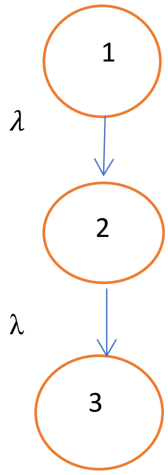


Figure 4A.5: Markov Model analysis for the M.E. Lube oil Strainer S

Table 4A.1: State of Lube oil strainer S

State of Lube oIl strainer S	Strainer 1	Strainer 2
1	Clean	Clean
2	Clogged	Clean
3	Clogged (Failed)	Clogged(Failed)

Table 4A.1 above shows3 states of S. In this case the two M.E. Lube Oil Pump Strainers are identical standby units, one of which is on line and the other on standby. The reliability of the two identical systems is derived as, $R_s(t) = e^{-\lambda t} \sum_{i=0}^{1} \frac{(\lambda t)^i}{i!}$.

In this case $R_s(t) = e^{-\lambda t}\ (1 + \lambda t)$ and MTTF (Mean time to failure) = 2/λ

4A.5 Reliability of the Main Engine Lube Oil System

The state diagrams for all other components of the system are analysed along the same lines, as for the suction strainer S. Markov analysis (Smith, 2011, Troyer, 2006), carried out to determine the reliability of the system components . Finally the reliability of the lubricating oil system is determined.

$\boldsymbol{R_{L.O.}(t) = R_s(t)R_p(t)R_F(t)R_{TCV}(t)R_{CLR}(t),}$

$\boldsymbol{where},$

$\boldsymbol{R_p(t)}$ is the reliability of the Pumps , ***Rs(t)*** is the reliability of the Strainer,

$\boldsymbol{R_F(t)}$ is the reliability of the Filter

$\boldsymbol{R_{TCV}(t)}$ is the reliability of the Temperature Control Valve

$\boldsymbol{R_{CLR}(t)}$ is the reliability of the Cooler.

4A.6 Improving Reliability

Reliability of the system can be improved by improving the component reliability as seen in the above equation. For instance, in the case of the Strainer S shown in Section 4A.4 above, physical introduction of an additional filter will increase the reliability. This cost for improvement of reliability needs to be assessed and the cost benefit for the incremental reliability determined. If the original value of Reliability R_O at cost x is improved to Reliability R_I at cost y, then the incremntal reliability for the differential cost $\frac{R_I - R_O}{y - x}$ should be compared with the base relaibility to cost ratio which in this case is $\frac{R_O}{x}$. For cost benefit $\frac{R_I - R_O}{y - x} > \frac{R_O}{x}$.

This could be a feasible proposition for some components, but not for all components. Similar study needs to be done for all other components and a cost beneficial CBM model could be developed.

Figure 4A.6 below shows the Reliability for two (2) identical suction strainers s and Figure 4A.7 shows the expected improved Reliability, when an additional suction filter is utilised. On similar lines means for improving Reliability for other components could be considered. Figure 4A.8 shows the improvement in reliability when a redundant filter is used and Figure 4A.11 shows the reliability improvement when an additional control valve is installed after the lubricating oil cooler. No additional redundancies were provided for the pumps and the cooler. This was obtained based on application of Markov's principle. Thus the overall Reliability for the Main Engine Lube Oil System could be evaluated, and improvement in reliability is shown, as seen in Figure 4A.12.

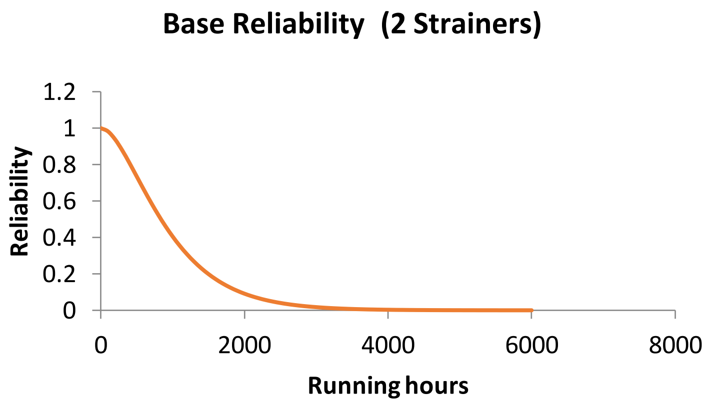


Figure 4A.6: Base Reliability vs running hours for two (2) Strainers

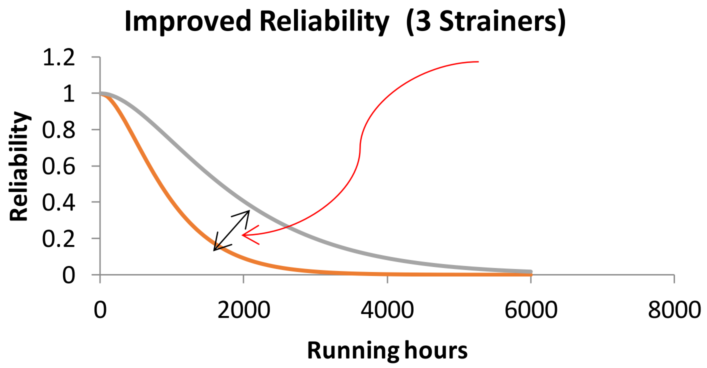


Figure 4A.7: Improved Reliability vs running hours for three (3) Strainers

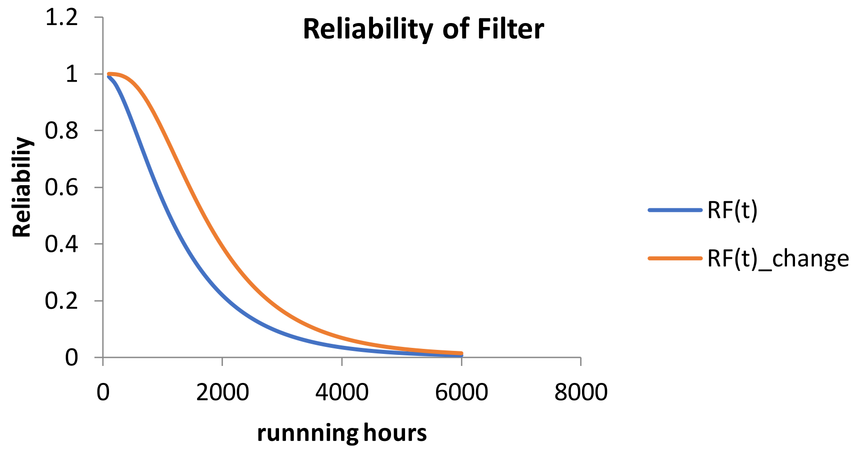


Figure 4A.8: Change in Reliability on addition of Lube oil filter

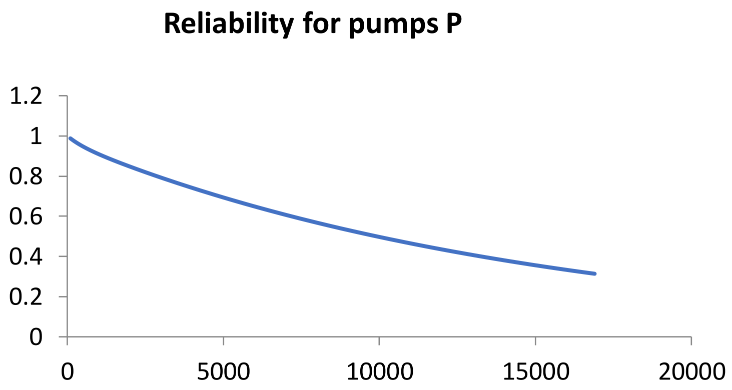


Figure 4A.9:Reliability for Lube oil pumps

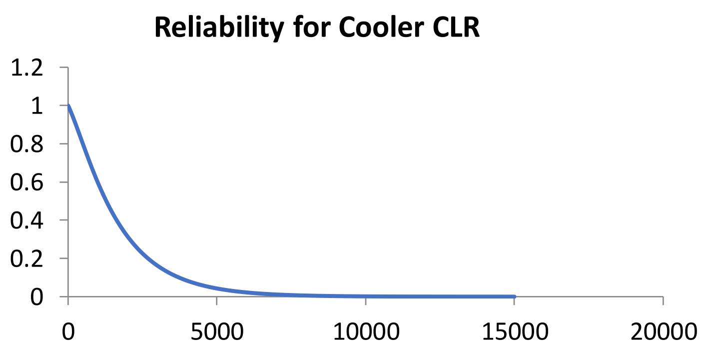


Figure 4A.10: Reliability for Lube Oil Cooler

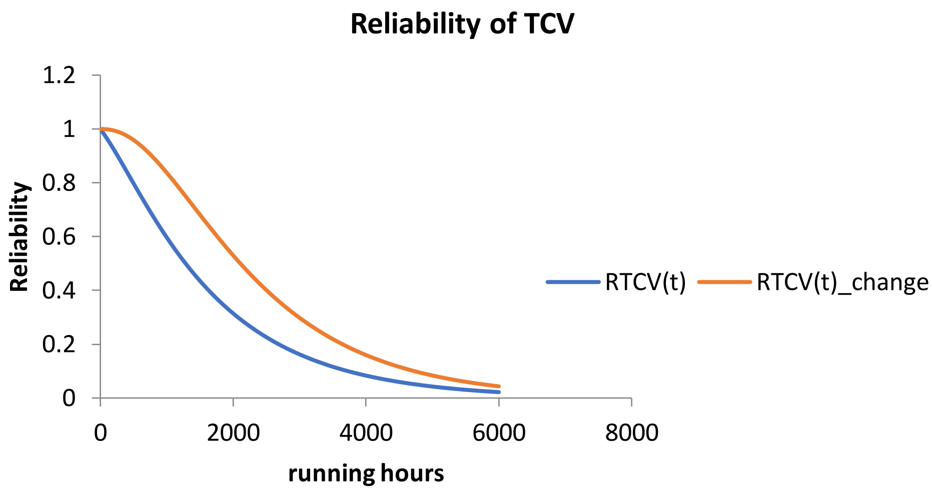


Figure 4A.11: Change in Reliability by addition of Temp Cont Valve

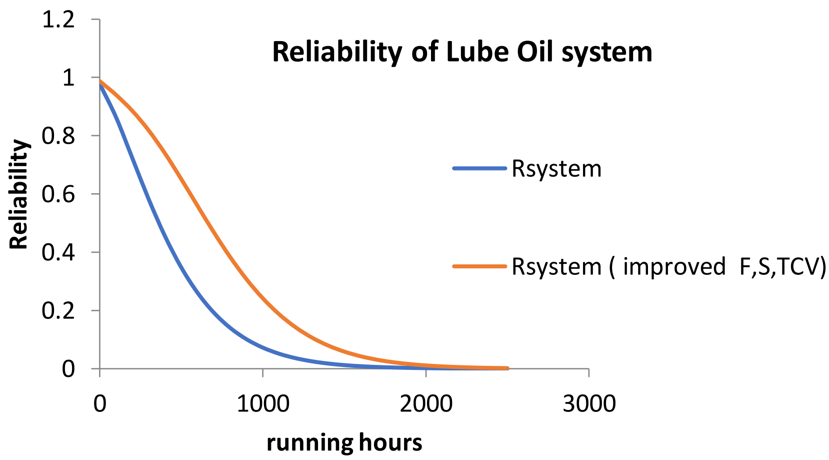


Figure 4A.12: Improved Reliablity for the Lube oil sysytem

4A.7 Conclusion

In this paper the Main Engine lubricating oil system, which is a very vital part of the Main propulsion system was analyzed. Failure of the Main Engine lubricating system may result in serious damage to the engine components and failure of the main engine. A step by step approach for evaluating the reliability of the Main Engine Lube Oil System was presented. Also, it was shown that use of additional components in the system, could provide improvement in the component reliability and contribute to overall reliability of the Main Engine Lubricating Oil System. A similar process could be looked at to evaluate the reliability of other subsystems of the main propulsion engine. Next steps will involve a development of a reliability centered condition-based maintenance model for the main propulsion system and determine the cost of improved reliability.

Having done that a maintenance plan could be devised leading to a final development of a cost beneficial CBM model for the ship's propulsion system.

Chapter 4B has been removed for copyright or proprietary reasons.

It has been published as: Anantharaman, M., Khan, F., Garaniya, V., Lewarn, B., Reliability of fuel oil system components versus main propulsion engine: An impact assessment study, Safety of Marine Transport: Marine navigation and safety of sea transportation, CRC Press, A Weintrit & T Neumann (ed), 175-180. ISBN 978-1-138-02859-3 (2015)

5. A holistic approach to Reliability and Safety of the main propulsion engine and its subsystems

This chapter is in the form of 2 peer reviewed publications as mentioned below

5A. Reliability assessment of main engine subsystems considering turbocharger failure as a case study.

Safe operation of a merchant vessel is dependent on the reliability of the vessel's main propulsion engine. Overall reliability of the main propulsion engine is interdependent on the reliability of several subsystems including lubricating oil system, fuel oil system, cooling water system and scavenge air system. The reliability of various components of certain systems such as gear pumps in a fuel oil system or filters in a lubricating oil system, which exhibit constant failure rate (random failure) independent of their history of operation, could therefore be analysed using Markov modelling. Other vital components such as turbochargers exhibit time dependent failure rate (wearing out). The wearing out failure rate (increasing failure rates) can be analysed using Weibull distribution. This paper presents integration of Markov model (for constant failure components) and Weibull failure model (for wearing out components) to estimate the reliability of the main propulsion engine.

5B. A holistic approach to Reliability and Safety on the operation of a main propulsion engine subjected to a harsh working environment.

This integrated model will provide a more realistic and practical analysis. It will serve as a useful tool to estimate the reliability of the vessel's main propulsion engine and make efficient and effective maintenance decisions. Moreover, this chapter represents the reliability assessment under harsh working environment. Because, the main propulsion engine of a vessel sometimes has to operate under harsh environmental conditions, for example very rough weather, there may occur concurrent failure of one or more units and failure of one or more subsystems of the main engine. Such failures on high seas could lead to disastrous consequences, which could include damage to ship's machinery, injury and/or fatality of shipboard personnel and pollution of the sea. Reliability and safety of the main propulsion engine needs to be looked at holistically when the main engine operates under harsh environmental conditions. Mathematical modelling for computing reliability of the main propulsion engine, combined with a relevant safety check list for the engine room, based on expert elicitation could be a good solution for an unremarkable voyage of the vessel under a harsh scenario. This paper intends to look at the harsh scenario for a bulk carrier propelled by a large main propulsion engine and arrive at a plan for a safe and reliable voyage of the vessel.

5.A Reliability assessment of main engine subsystems considering turbocharger failure as a case study

5A.1 Abstract

Safe operation of a merchant vessel is dependent on the reliability of the vessel's main propulsion engine. Reliability of the main propulsion engine is interdependent on the reliability of several subsystems including lubricating oil system, fuel oil system, cooling water system and scavenge air system. Turbochargers form part of the scavenge subsystem and play a vital role in the operation of the main engine. Failure of turbochargers can lead to disastrous consequences and immobilisation of the main engine. Hence due consideration need to be given to the reliability assessment of the scavenge system while assessing the reliability of the main engine. This paper presents integration of Markov model (for constant failure components) and Weibull failure model (for wearing out components) to estimate the reliability of the main propulsion engine. This integrated model will provide more realistic and practical analysis. It will serve as a useful tool to estimate the reliability of the vessel's main propulsion engine and make efficient and effective maintenance decisions. A case study of turbocharger failure and its impact on the main engine is also discussed.

Key words: Main propulsion engine, Scavenge system, Turbocharger, Reliability analysis, Markov model, Weibull model.

The demand for large capacity vessels in commercial shipping has increased over the last decade. These large vessels are propelled by powerful marine diesel engines.It is imperitive that the main engine should have high reliability for safe opeartion of the vessel. The reliability of a vessel's main propulsion engine is dependent on a number of essential sub systems, including fuel oil system, lubricating oil system, cooling water system and scavenge air system. Each of this subsystem has its own individual system components, the reliability of them would dictate the reliability of the corresponding subsystem, (EPSMA, 2005; Mollenhauer & Tschöke, 2010). Turbochargers form a very important part of the scavenge system and it is essential that the turbochargers have high reliability to ensure reliability of the main engine, (Takashi, 194). Failure of turbochragers could lead to disastrous consequences and imobilisation of the main engine. To determine the reliability of the various system components one need to look at the failure pattern depicted by these components. Previous studies have shown that most of the system components in commercial vessels, propelled by large two-stroke engine will fall in the second and third phase of the bath tub curve (shown in Figure 5A.1), which is a constant failure rate followed by an increasing failure rate, (Hashemian & Bean, 2011). The reliability of various components of some systems such as gear pumps in a fuel oil system or filters in a lubricating oil system, exhibits constant failure rate (random failure) independent of their history of operation, therefore they could be analysed using Markov modelling. Other major components such as turbochargers exhibits time dependent failure rate.

Phase 1 Infant Mortality, decreasing failure rate (Weibull Analysis)

Phase 2 Useful life, constant failure rate (Markov analysis)

Phase 3 Wear out, increasing (time dependent Weibull analysis)

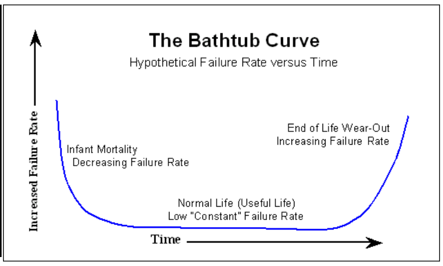


Figure 5A.1: Bath tub curve for failure rate

The wearing out failure rate can be analysed using Weibull analysis. This paper presents integration of Markov model (for constant failure components) and Weibull failure model (for wearing out components) to estimate the reliability of the main propulsion engine. This integrated model will provide more realistic and practical analysis. It will serve as a useful tool to estimate the reliability and make efficient and effective maintenance decisions. Reliability of Fuel oil, Lube oil and Scavenege air system is analysed below.

Figure 5A.2 below shows a reliability block diagram (RBD) for a main engine fuel oil sysytem. QC represents the Quick Closing valve, FS represents the Fuel Supply pumps, FL is the Discharge filters, FM is the Flowmeter, BT is the Buffer tank, BP represents the Booster pumps, HT represents the steam heater and VIS the Viscotherm. The next step is the analysis of evaluating the reliability of the main engine fuel oil system, by using Markov analysis(Gowid, Dixon, & Ghani, 2014).

Tthe following points are taken into consideration.

1. Each block represents the maximum number of components in order to simplify the diqgram.

2. The function of each block is easily identified
3. Blocks are mutually independent in that failure of one should not affect the probability of failure of another, (Anantharaman, 2013; Xu, 2008), (Bhattacharjya & Deleris, 2012).

Figure 5A.2: RBD for Main Engine Fuel Oil System

5A.2 Reliability of the Quick Closing Valve

The quick closing valve is the main tank outlet valve, which can be operated remotely in case of an emergency. If we assume a constant failure rate λ, (PCAG, 2012), then the reliability of this component may be expressed as;

$R_{QC}(t) = e^{-\lambda t}$, where the mean time to failure MTTF $= 1/\lambda$.

5A.3 Reliability of the Fuel Oil Supply pump FS

The fuel oil supply pumps FS are of the gear type and identical in design and construction. The reliability function is an exponential function of time t and the failure rate λ expressed as number of failures per running hours, (Bhattacharjya & Deleris, 2012).

Table 5A.1: State of Fuel oil supply pump

State	Pump 1	Pump 2
1	Operating	Standby
2	Failed	Operating
3	Failed	Failed

From above it is clear that there are 3 states. The two fuel oil supply pumps are identical units, Liberacki(2007), one of which is on line and the other standby. The reliability of two identical systems is derived as, $R_s(t) = e^{-\lambda t}\sum_{i=0}^{1}\frac{(\lambda t)^i}{i!}$.

In this case $R_s(t) = e^{-\lambda t}(1 + \lambda t)$ and MTTF (Mean time to failure) $= 2/\lambda$

Markov analysis is used to compute the reliability of the other componennts in the fuel oil system. The reliability of main engine fuel oil system will be given by

$$R_{F.O.}(t) = R_{QC}(t)R_{FS}(t)R_{FL}(t)R_{FM}(t)R_{BT}(t)R_{BP}(t)R_{HT}(t)R_{VIS}(t) \qquad \text{Equation (1)}$$

5A.4 Reliability of Lubricating oil system

The next step in the analysis of evaluating the reliability of the main engine lubricating oil sysytem is shown below:

The following five (5) cases s are analysed:

i. Failure of suction strainer S
ii. Failre of pumps P
iii. Failure of discahrge filter F
iv. Failure of Temperature Control Valve TCV
v. Failure of cooler CLR

Each block represents the maximum number of components in order to simplify the diqgram.The function of each block is easily identified. Blocks are mutually independent in that failure of one should not affect the probability of failure of another.(Anantharaman, 2013; Xu, 2008).

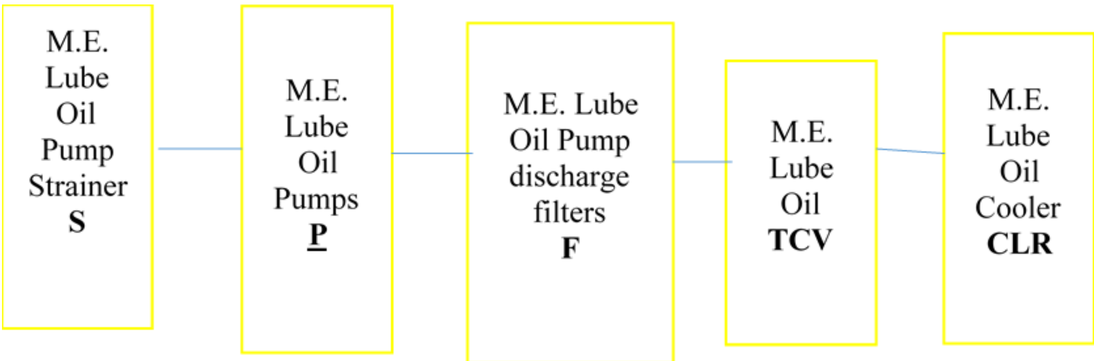


Figure 5A.3: Detailed RBD for M.E. Lube Oil system, with all system components

5A.5 State diagram for the Main Engine Lube Oil Strainer

The first component suction strainer S is a basket type strainer, located before the lubricating oil pumps, (Khonsari & Booser, 2008).This is a duplex type of filter with a changeover cock for isolation of filters. One of the filters is in use, the second one being a standby. Clogging of the strainer can result in pump's inability to draw suction from the sump, which may sound a low-pressure alarm. This provides time for changing over to the standby strainer. Failure of this change over will result in pump's inability to supply lubricating oil to the engine, finally resulting in an engine failure, (Cicek & Celik, 2013).These filters will be identical as shown in Figure 5A.4. The state diagram for the filters is shown in Figure 5A.5. The reliability functions an exponential function of time t and the failure rate λ expressed as number of failures per running hours , (Brandowski, 2009; Navy, 1994).

Figure 5A.4: Lube oil suction strainers for the Main Engine Lube oil system

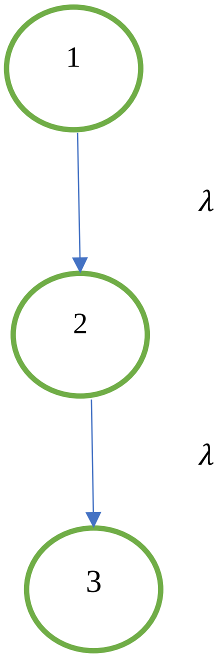


Figure 5A.5: Markov Model analysis for the M.E. Lube oil Strainer S

Table 5A.2 - State of Lube oil strainers

State	Strainer 1	Strainer 2
1	Clean	Clean
2	Clogged	Clean
3	Clogged (Failed)	Clogged(Failed)

As shown in Table 2, there are 3 states. In this case the two main engine lube oil pump strainers are identical standby units, one of which is on line and the other standby.The reliability of the two identical systems isderived as, $R_s(t) = e^{-\lambda t} \sum_{i=0}^{1} \frac{(\lambda t)^i}{i!}.$

In this case $R_s(t) = e^{-\lambda t}\ (1 + \lambda t)$ and MTTF (Mean time to failure) = 2/λ

5A.6 Reliability of the Main Engine Lube Oil System

The state diagrams for all other components of the system are analysed on the same lines, as done for the suction strainer S. Markov analysis(Smith, 2011; Troyer, 2006), carried out to determine the reliability of the system components . Finally the reliability of the lubricating oil system is determined(Liberacki, 2007).

$R_{L.O.}(t) = R_s(t)R_p(t)R_F(t)R_{TCV}(t)R_{CLR}(t)$ Equation (2)

$where$

$R_s(t)$ is the reliability of the Strainer

$R_p(t)$ is the reliability of the Pumps

$R_F(t)$ is the relaibility of the Filter

$R_{TCV}(t)$ is the reliability of the temperature control valve

$R_{CLR}(t)$ is the reliability of the cooler

5A.7 Reliability of a scavenge air system

Efficiency of a scavenge air system for a large propulsion engine consists mainly of an exhaust gas turbocharger (Takashi and Susumu, 1994), (Conglin Dong, 2013). The heat energy of the exhaust gas drives the exhaust gas turbine coupled to a rotary air compressor, which then draws air from the engine room. The compressor compresses the air which is then cooled in an air cooler before being sent to the engine cylinder. One such turbocharger is shown in Figure 5A.6. In short the turbocharger and the cooler form the main elements of the scavenge air system, failure of any one of the components could lead to failure of the main engine, as shown in the fault tree (Zhu, 2011), diagram in Figure 5A.7.

Figure 5A.6 Turbocharger for a large two stroke engine at test bed in QMD, Qingdao, China.

5A.8 Fault tree for Main Engine failure

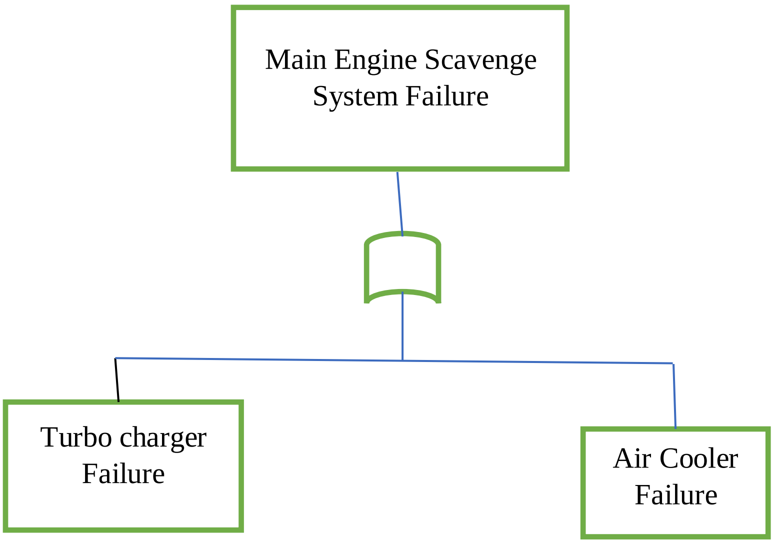
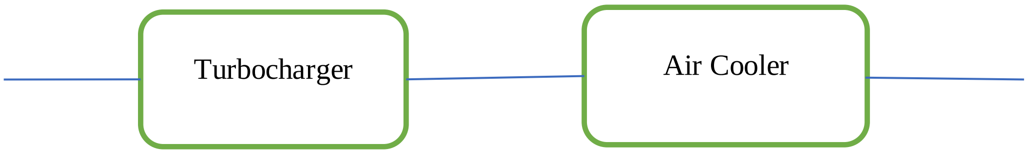


Figure 5A.7: Fault tree for a Main Engine Scavenge system

Failure of either the Turbocharger (ATSB,2006), or Air Cooler would result in failure of the Main Engine Scavenge system (Laskowski, 2015).

5A.9 RBD for Scavenge air system

A reliability block diagram for the scavenge air system is shown below.



$$R_{Scavenge} = R_{Turbocharger} * R_{Aircooler}$$

Figure 5A.8: RBD for Main Engine Scavenge system

The turbocharger and air cooler are in series, hence the reliability of the scavenge air system could be computed. These two components form a very robust part of the scavenge air system. Depending upon the engine capacity there could be one or more turbochargers or air coolers fitted to the main propulsion engine. This arrangement has more to do with the engine capacity and is not based on a redundancy factor.

5A.10 Reliability of the Turbocharger

The turbocharger assembly consists of air filter, blower casing, turbine casing, rotor and bearings (Schieman, 1992-1996). Modern turbochargers are manufactured with sleeve type bearings which have a very long operating life ranging up to 50,000 running hours (SE, 2017). Hence while determining the reliability of the turbocharger we need to look into the phase 3 of the bath tub curve, where the end of life wear out could be considered, needs to be looked at rather than the phase 1 or phase 2 of the bath tub curve. In the phase 3 the reliability of the Turbocharger may be computed using Weibull distribution (Dhillon, 2002). The Reliability of the Turbocharger could be expressed as a function of time t.

$\boldsymbol{R}_{\boldsymbol{Turbo}}(\boldsymbol{t}) = \boldsymbol{e}^{\left(-\frac{\boldsymbol{t}}{\boldsymbol{\theta}}\right)^{\boldsymbol{\beta}}}$ and the hazard rate function will be given by

$\boldsymbol{\lambda}_{\boldsymbol{Turbo}}(\boldsymbol{t}) = \frac{\boldsymbol{\beta}}{\boldsymbol{\theta}}\left(-\frac{\boldsymbol{t}}{\boldsymbol{\theta}}\right)^{\boldsymbol{\beta-1}}$

where θ is the scale parameter that influences both the mean and the spread or dispersion of the distribution and is the characteristic life and has units to those of time t, in this case hours, $\theta > 0$. β is referred to as the shape parameter and $\beta > 0$. The Weibull hazard rate function can be increasing or decreasing depending on the value of β. If $\beta = 1$,

$\lambda_{Turbo}(t)$ *is constant and equal to* $\frac{1}{\theta}$, the distribution being identical to the exponential.

5A.11 Reliability of the Air cooler

The air cooler plays a vital role in the scavenging system. The high temperature air discharged by the turbocharger needs to be cooled before sending it to the engine cylinders. These air coolers are generally sea water cooled, the sea water being passed through bronze alloy tubes, by means of a two pass cooling arrangement, to provide effective cooling of the charge air. The air flow will be one pass through the aluminium fins which are soldered to the brass alloy tubes, to avoid excessive pressure drop. Considering the reliability of the air cooler again the aging factor should be considered, hence phase 3 of the bath tub curvewill be considered. Along similar lines to detecting reliability of the turbocharger, the reliability of the air cooler may be computed using Weibull distribution (Kiriya, 2001). The reliability of the air cooler could be expressed as a function of time t.

$R_{\ Airclr}(t) = \ e^{\left(-\frac{t}{\theta}\right)^{\beta}}$ $and\ the\ hazard\ rate\ function\ will\ be\ given\ by$

$\lambda_{Airclr}(t) = \frac{\beta}{\theta}\left(-\frac{t}{\theta}\right)^{\beta-1}$ where θ is the scale parameter that influences both the mean and the spread or dispersion of the distribution and is the characteristic life and has units to those of time t, in this case hours, θ > 0. β is referred to as the shape parameter and β > 0.

5A.12 Reliability of the Scavenge air system

Both the turbocharger and air cooler, being in a serial configuration, need to function for the scavenge air system to function. Both components are critical and if either one of them fails, the scavenge system will fail. The combined Weibull system reliability can be computed as follows:-

$R_{scavenege\ air} = \prod_{i=1,2} e^{-(t/\theta_i)^{\beta_i}}$

where i=1 is the Turbocharger and i= 2 is the Air cooler. Equation (3)

5A.13 Reliability of the Main propulsion engine

The Reliability of the Fuel oil system has been determined by Markov analysis, Lubricating Oil system by Markov analysis (both modelled using constant failure rate principle) and also the Reliability of Scavenge air system has been determined as a time dependent failure model, and we are now positioned to determine the Reliability of the Main propulsion engine as follows:

$R_{MainEngine} = \prod R_{i\ i=1,2,3,}$ Equation (4)

i = 1 is the fuel oil system from Equation 1 (Markov modelling)

i = 2 is the lubrictaing oil system from Equation 2 (Markov modelling)

i = 3 is the scavenge air system from Equation 3 (Weibull modelling)

Improving Reliability

Reliability of the main engine can be improved by improving the individual system reliability as seen in the above Equation 4 . For instance in the case of the scavenge air system, a modern high performance turbocharger will improve the reliability of the turbocharger.This cost for

improvement of reliability needs to be assessed and the cost benefit for the incremental reliability be determined. If the original value of reliability R_O at cost x is improved to reliability R_I at cost y, then the incremntal reliability for the differential cost $\frac{R_I - R_O}{y - x}$ should be compared with the base relaibility to cost ratio which in this case is $\frac{R_O}{x}$.
For cost benefit $\frac{R_I - R_O}{y - x} > \frac{R_O}{x}$.

This could be a feasible proposition for some components, but not for all components. Additionally an appropriate maintenance program to strike the right balance between reliability required and the cost penalty likely to be incurred could be looked at. Attention is drawn to the air cooler in the scaveneg air system as an example. All modern air coolers manufactured by major engine manufactureres have an incorporated cleaning in place system for maintenance of air coolers which involves no dismantling of the air cooler whilst carrying out maintenance (Balbir S Dhillon, 2002). Accordingly the maintenance intervals for air coolers could be shorter, at the same time increasing the maintenance intervals of turbochargers and still provide a more effcient and reliable main engine.

5A.14 Case study of Turbocharger failure on a merchant vessel

An interesting case study of a main engine turbocharger failure, which could lead to disastrous consequenes, resulting in stoppage of a main engine at sea shall be studied. Turbochargers play a great role in the operation of the main engine, hence reliability of the main engine is dependent to a large extent on the reliability of turbochargers (Heim, 2002). An important factor to be taken into consideration is the matching of the turbocharger to the main propulsion engine (Hountalas, 2000). Since the main propulsion slow speed engine and the turbochargers are normally manufactured by two different manufacturers, experts in their own field, it is inevitable that there could be an issue on the conceptual thinking between the two parties. However any matching discrepancies need to be sorted out during the ship’s sea trial. Any mismatch could be corrcetd by replacment of the diffuser or nozzle ring (Kim, Park, Ryu, Choi, & Ghal, 2009).

The case study refers to a vessel at sea and the investigation carried out by the Australian Transport Safety Bureau (Australian Transport Safety Bureau, 2006). The investigation refers to a bulk carrier powered by a large two stroke engine with a rated power of 6400 kW, propelling at 14.5 knots. On two ocasions, within a span of less than 5 months, the vessel suffered serious damage due to failue of the turbocharger.. The exact cause of the damage was not available, but in both cases the failure followed a large engine scavenge fire. Figure 9 below shows the extent of the serious damage to the turbocharger rotor, resulting in immobilisation of the main engine (Takashi, 194).

Figure 5A.9: Damaged turbocharer rotor shaft
(Courtesy : ATSB Investgations 186 and 191)

5A.15 Conclusion

In this paper we have looked at methods of determining the reliability of three subsystems of a vessel's main engine which includes the fuel oil system, lubricating oil system and the scavenge air system have been looked at. The fuel oil and lubricating oil sytem was modelled by Markov analysis and the scavenge air system was analysed using Weibull distribution which is a time dependent failure model. An attempt has been made to make reliability assessment of a vessel's main engine by combining Markov analysis integrated with time dependent failures.The incremental reliability to incremental cost ratio for the main engine, which should always be greater than the original reliability to original cost ratio, for cost benefits in the long run has also been discussed. Finally some examples of effectively altering the maintenance intervals of certain system components, whereby the overall reliability of the system could be improved were looked at.

A case study of turbocharger failure on a merchant vessel was studied and it was shown that the turbocharger failure can have a major impact on the main engine operation, leading to immobilisation of the main engine. Hence matching of the turbocharger and main engine is especially critical for safe and reliable operation of the main engine.

5B. A holistic approach to Reliability and Safety on the operation of a main propulsion engine subjected to a harsh working environment.

Abstract

The main propulsion engine of a vessel operates under harsh environmental conditions that include very rough weather, concurrent failure of one or more units of the engine and failure of one or more subsystems of the main engine. Such failures on high seas could lead to disastrous consequences, which could include damage to ship's machinery, injury and/or fatality of shipboard personnel and pollution of the sea. Reliability and Safety of the main propulsion engine needs to be looked at holistically when the main engine operates under harsh environmental conditions. Mathematical modelling for computing reliability of the main propulsion engine, combined with a relevant safety check list for the engine room, based on expert elicitation could be a good solution for an unremarkable voyage of the vessel under a harsh scenario. This paper intends to look at the harsh scenario for a bulk carrier propelled by a large main propulsion engine and arrive at a plan for a safe and reliable voyage of the vessel.

Keywords: Holistic, reliability, safety, harsh, bulk carrier, expert elicitation.

5B.1 Introduction

Reliability and Safety are two vital factors when it comes to operation of a main engine propelling large capacity modern bulk carriers in high seas. A main propulsion engine is associated with several subsystems for its operation. The subsystems are the main engine lube oil system, the main engine fuel oil system, the main engine cooling water system and the scavenge system. The reliability of the main propulsion engine is dependent on the reliability of its subsystems (EPSMA, 2005; Mollenhauer & Tschöke, 2010). Various methods could be adopted to determine the reliability of the subsystems depending upon the failure rate exhibited by the system components (B. S. Dhillon, 2002). A combination of constant failure rate and time dependent failure rate modelling was used to determine the reliability of the subsystems (Xie & Lai, 1996). Thus, the reliability of the main propulsion engine is determined. A mathematical model can determine the reliability of the main engine propelling a bulk carrier under normal sea condition. However, when the bulk carrier is subjected to harsh environmental conditions, additional factors to ensure safety of the vessel need to be considered. The harsh environmental condition mainly comprises bad weather where the main engine could encounter failure of one or more cylinders, thereby necessitating operation of the engine at a reduced load to get the vessel to safe heaven. There is also the likelihood of failure of the ship's power generation machinery under a harsh working environment, which would be a matter of very high concern relating to the safe operation of the vessel. When it comes to running a bulk carrier, it is also vital that both the ballast and the loaded condition are considered, when the operating conditions are different (Krüger, Steinbach, Kaufmann, & John, 2010). This paper aims to investigate all the above factors and ensure safe operation of the bulk carrier under a harsh working environment.

5B.2 Reliability

Reliability of the main engine for the safe and remarkable voyage of a bulk carrier

$\mathbf{R_{MEN}}$: Reliability of the min engine at normal power

P_{nor}: Main Engine normal power

S_v : Safe voyage

$S_{chk:}$ Safety check list

P_{red}: Main Engine reduced power

R_{MEH} : Reliability of the main engine in harsh environment

R_v : Remarkable voyage

A bulk carrier is a vessel which carries cargo in bulk, which could be grain, coal, industrial salt or iron ore, to name a few. The cargo carrying capacity of a bulk carrier may vary between 3,000 dwt and 400,000 dwt. Generally, these bulk carriers are propelled by large two stroke marine diesel engines, referred to as the main engine. The reliability of the main propulsion engine R_{MEN} will be dependent on the reliability of several of its subsystems, which include the lubricating oil system, fuel oil system, scavenge system and cooling water system. The main engine will be generating its normal power P_{nor}, when the bulk carrier is operating in gentle environmental conditions. Markov and Weibull modelling (Richard E Brown, 2004; Srinivasa Rao & Naikan, 2016),(Duffey & Van Dorp, 1999) techniques have been used to determine the reliability of various main engine sub systems and having done so, the reliability of the main engine could be determined from the reliability block diagram (RBD) as shown in Figure below. 5B.2

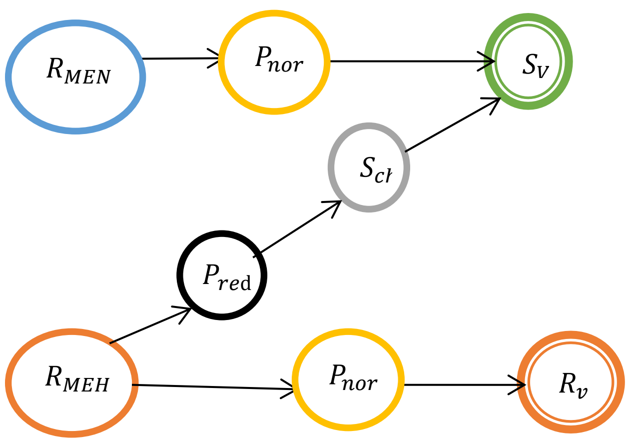


Figure 5B.1: Events comparing a safe voyage and a remarkable voyage for a bulk carrier

5B.3 Reliability block diagram (RBD) for main engine evaluating reliability of main engine

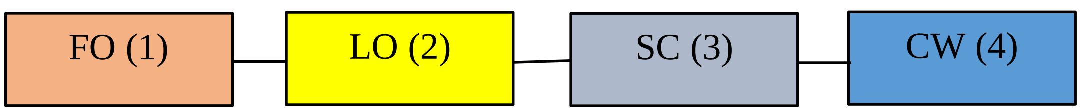


Figure 5B.2: Reliability block diagram for main engine

$$R_{MEN} = \prod R_{i_{i=1,2,3,4}} = \prod R_{i_{i=LO,FO,SC,CW}}$$

i= 1 is the fuel oil system (Markov modelling) i =2 is the lubricating oil system (Markov modelling)

i= 3 is the scavenge air system (Weibull modelling)

i = 4 the cooling water system (Markov modelling)

A safe uneventful voyage of the bulk carrier is denoted as Sv. Hence the safe voyage of the bulk carrier;

$$S_v = f(R_{MEN}, P_{nor})$$

On the other hand when the bulk carrier is subjected to a harsh environment at sea this could be an entirely different scenario. The safety features of bulk carriers have been highlighted by the IMO (International Maritime Organization, www.imo.org, 01.05.2017), in their work on Bulk Carrier Safety and this includes safe loading, discharging and carriage of bulk cargo. It also features the various safety measures employed in the safe design of bulk carriers. Also based on extensive research, IMO has prescribed additional measures for bulk carrier safety in SOLAS (Safety Of Life At Sea). Accordingly, when subjected to a harsh working environment, the bulk carrier needs to account for several factors, to ensure a safe voyage. In failing to account for the necessary factors, the end result could be a remarkable voyage. The main factors which could add to a remarkable voyage R_v would include, R_{MEH}, the reliability of the main engine under harsh environmental condition, Pnor the normal power of the main engine, which is the same as that when the main engine is operating in a gentle environmental condition.

To ensure a safe voyage for the bulk carrier under a harsh working environment, it is absolutely necessary for the main engine propelling the bulk carrier to be run at reduced power P_{red} to ensure safety of the hull, machinery and the ship's crew (Khan & Haddara, 2003). It is also necessary to develop a safety check list $S_{chk:}$ based on expert elicitation to eliminate the possibility of an eventful or remarkable voyage Rv.

$$R_v = f(R_{MEH}, P_{nor})$$

A safe voyage in a harsh working environment could be represented as shown below

$$S_v = f(R_{MEH}, P_{red,} S_{chk})$$

$$R_{MEN} = \prod R_{i_{i=1,2,3,4}} = \prod R_{i_{i=LO,FO,SC,CW}}$$

The power developed by the main engine under normal operation will be proportional to the reliability under normal operation. This is mathematically stated below as

$$P_{nor} \propto R_{MEN} \;\therefore P_{nor} \propto \prod R_{i_{\,i=LO,FO,\,SC,CW}} \quad \text{or}$$

$$P_{nor} \propto R_{LO} * R_{FO} * R_{sc} * R_{cw}$$

When subjected to a harsh working environment, the main engine should be run at a reduced load, to keep the load variation to a minimum, failing to do so may lead to major damage to the engine components and components of the subsystems. At reduced load the power developed will be reduced P_{red} and it is assumed that this will be proportional to the reliability of the main engine at the reduced reliability for a harsh environment and as mathematically stated below; $P_{red} \propto R_{MEH}$.

Table 5B.1: Reliability compensating factor k_i

Main Engine Subsystem	System components	Type of failure	Reliability compensating factor
Main Engine Lube oil system	Lube oil filters	Partial and total clogging of filters	$\mathbf{k_{lf}}$
	Lube oil pumps	Tripping of pumps due to overload	$\mathbf{k_{lp}}$
Main Engine Fuel oil system	Fuel oil tank quick closing valve	Abrupt closing of valve	$\mathbf{k_{fq}}$
	Fuel oil filters	Partial and total clogging of filters	$\mathbf{k_{ff}}$
	Fuel oil pumps	Tripping of pumps due to overload	$\mathbf{k_{fp}}$
	Fuel oil temperature control vale	Malfunction of control valve	$\mathbf{k_{ft}}$
Main engine Scavenge System	Turbochargers	Surging	$\mathbf{k_{sc}}$
Main Engine Cooling water system	Pumps	Tripping of pumps due to overload	$\mathbf{k_{cwp}}$
	Cooling water temperature control valve	Malfunction of control valve	$\mathbf{k_{cwt}}$

5B.4 Load reduction factor k and reliability compensation factor k_i

We define a load reduction factor k and a reliability compensating factor to evaluate R_{MEH} . A load reduction factor which is the ratio of the normal power to the reduced power of the main engine in a harsh environment $\frac{P_{red}}{P_{nor}}$ =k. We would also like to define a reliability compensating factor k_i, under an assumption that the reliability at the reduced load in a harsh working environment is a function of the load reduction factor k. Since reliability of any of the main engine subsystem components are a function of its failure rate λ, it is reasonable to assume that the reliability at a reduced load will have a failure rate $\frac{\lambda}{k}$.

$$\mathbf{R_{MEH} = k_{lf}k_{lp}R_{LO} * k_{fq}k_{ff}k_{fp}k_{ft}R_{FO} * k_{sc}R_{sc} * k_{cwp}k_{cwt}R_{cw}}$$

$$\mathbf{\frac{P_{red}}{P_{nor}} = \frac{R_{MEH}}{R_{MEN}} = \frac{kP_{nor}}{P_{nor}}}$$

$$\frac{\mathbf{k_{lf}k_{lp}R_{LO} * k_{fq}k_{ff}k_{fp}k_{ft}R_{FO}} * k_{sc}\mathbf{R_{sc} * k_{cwp}k_{cwt}R_{cw}}}{\mathbf{R_{LO} * R_{FO} * R_{sc} * R_{cw}}}$$

$$\boldsymbol{k} = \frac{\mathbf{k_{lf}k_{lp}R_{LO} * k_{fq}k_{ff}k_{fp}k_{ft}R_{FO} * k_{sc}R_{sc} * k_{cwp}k_{cwt}R_{cw}}}{\mathbf{R_{LO} * R_{FO} * R_{sc} * R_{cw}}}$$

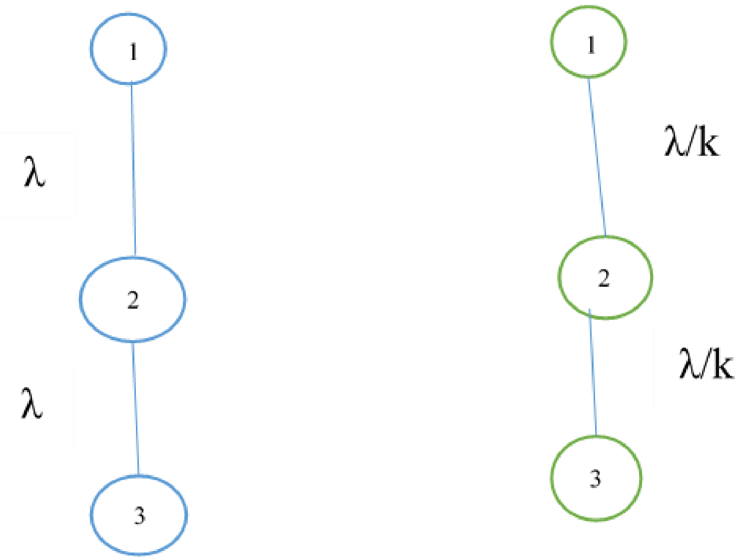
which gives us $\mathbf{k = k_{lf}k_{lp} * k_{fq}k_{ff}k_{fp}k_{ft} * k_{sc} * k_{cwp}k_{cwt}}$

5B.5 Sample calculation of reliability compensator factor k_{lf} for main engine lube oil filter

Table 5B.2: State diagram for lube oil flter

State	Filter 1	Filter 2
1	clean	clean
2	clean	clogged
3	clogged	clogged

Figure 5B.3: Lube oil suction strainers for the main engine lube oil system



Gentle environment Harsh environment

Figure 5B.4: State diagram for lube oil filter

As shown in Table 2, there are 3 states. In this case the two main engine lube oil pump strainers are identical standby units, one of which is on line and the other on standby.The reliability of the two identical systems is derived as, $R_f(t) = e^{-\lambda t} \sum_{i=0}^{1} \frac{(\lambda t)^i}{i!}$.

In this case $R_f(t) = e^{-\lambda t} (1 + \lambda t)$ and MTTF (Mean time to failure) $= 2/\lambda$

The above equation holds for gentle environmental condition of the main engine lubricating oil subsystem. When subjected to a harsh working environment an assumption is made that the failure rate of the engine component will be proportional to the reduced power P_{red} on the main engine. The modified reliability for the lube oil filter can be shown to be

$$R_{fh}(t) = e^{-\frac{\lambda t}{k}} \left(1 + \frac{\lambda t}{k}\right)$$

where k is the reduction load factor, which must be adjusted in a harsh working environment.

The reliability compensating factor for the lube oil filter may then be determined as follows:

$$\mathbf{k_{lf}} = \frac{\mathbf{R_{fh}(t)}}{\mathbf{R_f(t)}} = \frac{\mathbf{e^{-\frac{\lambda t}{k}} \left(1 + \frac{\lambda t}{k}\right)}}{\mathbf{e^{-\lambda t} (1 + \lambda t)}} = \frac{\mathbf{\left(1 + \frac{\lambda t}{k}\right)}}{\mathbf{e^{\frac{1}{k}} (1 + \lambda t)}}$$

On the same lines the reliability compensating k factors for the other system components could be determined. We would expect the product of all the reliability compensating values to be close to the reduction load factor of the main propulsion engine under a harsh working environment.

5B.6 Markov modelling for lube oil

Table 5B.3: Reliability of lube filters

Reliability of Lube oil filters	
λ = 4.53*10^-6, t =2000 hrs	
R(lf) at normal load e^(-λt)(1+λt)	
R(lf) at reduced load k e^(λ/kt)(1+λ/kt)	
K	R(lf)
1	0.999959
0.9	0.99995
0.8	0.999936
0.7	0.999917
0.6	0.999887
0.5	0.999838
0.4	0.999747
0.3	0.999553
0.2	0.999004
0.1	0.996136
Klf	0.996176

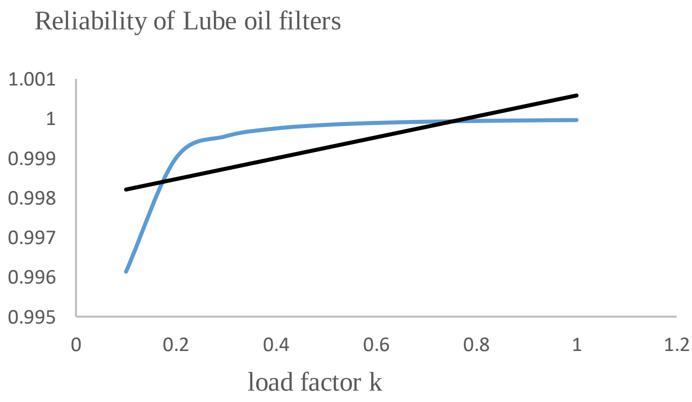


Figure 5B.5: Reliability vs load factor of lube oil filters

5B.7 Weibull modelling for Turbocharger

Tabe 5B.4: Reliability of Turbochargers

t months	Shape factor β=3	Scale factor θ	Reliability at β=3	Shape factor β=1	Reliability at β=1
10	3	200	0.999875	1	0.951229
20	3	200	0.999000	1	0.904837
30	3	200	0.996630	1	0.860708
40	3	200	0.992031	1	0.818730
50	3	200	0.984496	1	0.778800
60	3	200	0.973361	1	0.740818
70	3	200	0.958031	1	0.704688
80	3	200	0.938005	1	0.67032
90	3	200	0.912903	1	0.637628
100	3	200	0.882496	1	0.606530

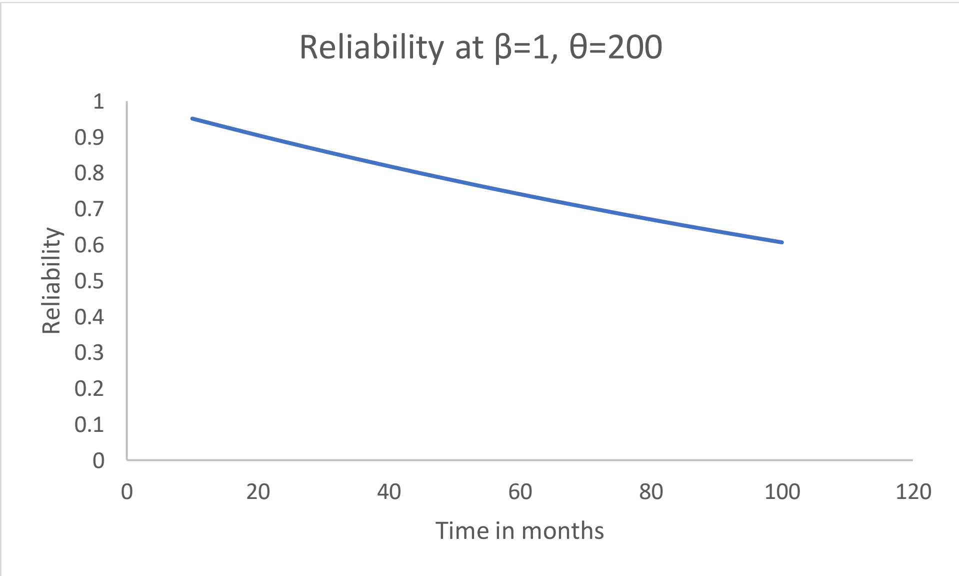


Figure 5B.6: Reliabiity vs time of Turbocharger

5B.8 Safety Aspects

In Table 5B.3 , the reliability compensating factor was calculated as a ratio of R(lf) at 0.1 % of normal load to R(lf) at normal load and the value of klf was 0.96176. Similar analysis was done for all other system components. The derivation of the formula for k in 2.3 above was based on the assumption that at reduced load compromise on reliability is needed. However, calculations from available data have shown that the safety aspect may have a major impact on the vessel's operation in a harsh environment. A case study of vessel accidents from the Australian Transport Safety Bureau (ATSB) data (ATSB, 2003, 2011, 2012, 2016) were analysed in this study and tabulated as shown in Table 5 below.

Table 5B.5: Vessel accidents sourced from the Australian Transport Safety Bureau (ATSB)

Year	**Vessel**	**Weather**	**Damage**	**Reason**
2010	1	HW	Loss of cargo	Lack of training of ship's crew in handling cargo lashing
2011	2	GW	Serious burns sustained by crew member	Breathing Air compressor explosion on deck
2011	3	P	Serious injury to crew member	Damaged catwalk in the machinery space
2010	4	GW	Damage to vessel	Collison between a bulker and another vessel
2012	5	P	Damage to cargo	Fire on deck
2011	6	HW	Vessel abandoned	Steering failure
2016	7	HW	Minor damage to ship's structure	Mooring damage
2012	8	HW	Drifting of vessel	Black out and engine failure
2012	9	GW	Serious injury to crew members	Explosion of auxiliary machinery
2012	10	GW	Grounding of vessel	Steering failure
2014	11	HW	Vessel touching the wharf	Propeller control system failure

HW (Harsh Weather) GW (Gentle Weather) P (Port)

5B.9 Safety check list

A safety check list has been developed based on ATSB research and expert elicitation (Roberts, Pettit, & Marlow, 2013).This will be useful to perform a safe voyage of the vessel under a harsh environment.

Table 5B.6: Engine Room Safety check list for a safe voyage

Sample check list for harsh environment	
Main engine lube oil system	Lubricating oil system Filters to be cleaned irrespective of PMS hours
Main engine fuel oil system	Check functioning of quick closing valve, temperature control valve irrespective of PMS hours
Main engine scavenge system	Clean air inlet filters, replenish oil in the lube oil sump both on turbine and blower side.
Main engine cooling water system	Check function of temperature control and continuously monitor expansion tank level
Steering gear system	Standby pump to be running, replenish oil in the sytem tank.
Auxiliary engine	Additional diesel generator to be running and sharing load of the plant.
Engine Room gear	Overhead crane to be lashed and no loose gears.

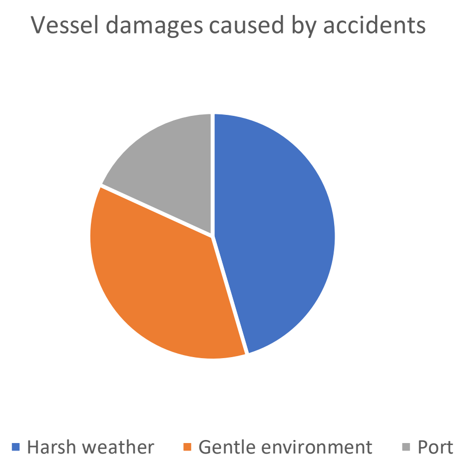


Figure 5B.7: Vessel damage caused by accidents

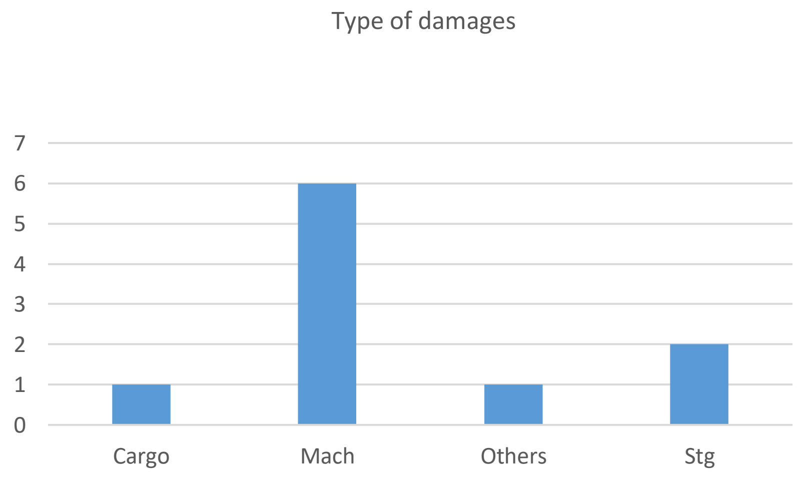


Figure 5B.8: Accident analysis (courtesy Australian Transport Safety Bureau (ATSB)

5B.10 Conclusion

In the above paper the two main aspects, reliability and safety, on the operation of a bulk carrier under harsh working environment have been looked at. The reliability of the main engine ranging from 10% to 100% load has been compared, assuming that the reliability is proportional to the load, and a reliability compensating factor for the main engine system components, in a harsh working environent has been evaluated.It could be concluded that the impact of harsh working environment per se does not impact reliability to a great extent. Other factors related to safety which should include cargo stowage, steering failure and failure of other auxiliary machinery, apart from the main engine failure need to be looked at and a holistic approach to reliability and safety taken, whilst operating the main engine in a harsh environment. This calls for further analysis, evaluation and quantification of the safety factors to ensure a safe voyage takes place. A safety check list for a safe voyage of the bulk carrier is also presented, based on research and expert elicitation.

6. Data-driven reliability model for marine engines

Abstract

Shipping is the life blood of the global economy. Today, about 90% of world trade happens by international shipping through over 50,000 merchant ships. These ships transport various types of cargo and are manned globally by over a million seafarers. Ships are technically sophisticated, high value assets (larger hi-tech vessels can cost over USD 200 million to build), and the operation of merchant ships generates an estimated annual income of over half a trillion US Dollars in freight rates. The majority of these ships are propelled by marine diesel engines due to its reliability and fuel efficiency. However numerous accidents take place due to failure of marine engines. Inappropriate maintenance plan is one of the main causes of failure of marine engines on board. In order to make better maintenance plans it is necessary to assess the reliability of the marine engines. However, there is a lack of appropriate data and model to fit the data. The engine manufacturers provide information for carrying out planned maintenance of engine components at specified running hours, without taking into consideration any of health condition. Moreover, the shipping companies have a limited technical ability to record the data correctly and use them effectively. In this study relevant data, collected from various sources, are analysed to identify the most appropriate failure model representing a specific component. The collected data and model developed will be very useful to assess the reliability of the marine engines and to plan the maintenance activities on-board the ship. As a result, this will help reduce the failure of marine engines and contribute towards reducing accidents in the shipping industry.

Keywords: Data collection, Analysis, Reliability analysis, Marine engine.

6.1 Introduction

Today modern merchant vessels have a huge cargo carrying capacity. Very large bulk carriers (VLBC) carry iron ore up to a full capacity of 400,000 DWT (dead weight tonnes). Ultra large crude oil carriers (ULCC), have an oil carrying capacity of 500,000 DWT. The world's largest container vessel has a capacity of 20,568 twenty-foot equivalent unit (TEU) containers. Moreover, liquid natural gas (LNG) has a large vessel of the tonnage 128,900 DWT, with a cubic capacity of 266,000 cubic metres. These huge vessels are propelled by large capacity marine diesel engines referred to as a main engine. The main engine is capable of producing power to the tune of 100 MW (megawatts).

In order to safely transport cargo from one port to another, it is important to make sure the main engine propelling these giant vessels is safe and reliable. Moreover, it is an ongoing challenge for commercial shipping operators to deal with issues related to the protection of environmental and legal implications on a day to day basis (Hatzigrigoris et al., 2005). Numerous marine accidents have occurred due to the failure of main engines. In August 2001, a Hong Kong flagged, cellular container ship of 44,153 deadweight tonnes, "*Maersk Tacoma*", had an accident at sea due to the failure of the lubricating oil system of a main engine (ATSB, 2001). In July 2006 the Antigua and Barbuda registered self-discharging bulk carrier "*Enterprise*" had an accident due to the failure of the lubricating oil system of a main engine while en-route from Adelaide to Sydney, Australia. As a result of this failure, the main engine stopped and caused the blackout of the ship at sea, and the ship had to be towed to the nearest port for repairs. The Australian Transport Safety Bureau (ATSB) investigation identified that maintenance planning for the main lubricating oil pump was inadequate and engineers did not follow the manufacturer's instructions, despite the fact that the pump had failed previously. Also, the execution of routine maintenance on the lubricating oil filter was inadequate in that the spare filter was not ready for use. The shipboard procedures did not identify the error and the procedures for operating and monitoring the filter were also ineffective (ATSB, 2006). In 2014, a passenger ferry "*Pride of Canterbury*" suffered a major fire in the engine room due to a damaged hydraulic pipe joint that caused the oil to spray on the exhaust manifold of the engine initiating the fire. The fire resulted in significant damage to the engine room (MAIB, 2014). In April 2008, "*Queen of the West*" a passenger vessel, had a fire in the engine room due to the failure of a pressurised component on the engine's hydraulic system. As a result of this accident, major damage to the tune of USD 3.9 million and one crew member was treated for mild hypothermia (NTSB, 2008). In October 2014, the uninspected towing vessel "*Dennis Hendrix*" was transiting upbound on the lower Mississippi River while pushing 24 loaded barges when a fire broke out in the engine room. The accident occurred due to the failure of the vessel's main propulsion engine resulting from loose bolts on the cylinder rod cap of one the engine cylinder units. Due to this failure, there was major damage to the engine parts which cost USD 3.8 million. However, none of the crewmembers was injured (NTSB, 2014). A cruise ship "*Carnival Liberty*" had an engine room fire in September 2015. The probable cause of this accident was loosened bolts, likely resulting from improper tightening during prior maintenance and vibration of the piping over time on a fuel supply inlet flange on the engine (NTSB, 2015). Due to this accident, estimated property damage was USD1.725 million. However, there was no injury to any crew member. The Transportation Safety Board (TSB) of Canada reported an engine room fire in 1994 on a self-unloading bulk carrier "*Nanticoke*" whilst at sea. The fire was caused by a leakage of fuel from the forward fuel filter on the port generator, which contacted an exposed exhaust manifold. Contributing to the occurrence was the modification to the fuel filter cover, the re-use of the copper sealing gasket on the cover, the unshielded hot exhaust surfaces adjacent to the filter, and the less than adequate engine-room watchkeeping duty during the fire drill before the occurrence (TSB, 1999).

Finally, in February 2010 at Gladstone, Queensland, an Australian registered bulk carrier "*River Embley*" had an engine room fire. The ATSB, revealed the events which led to the engine room fire, which was initiated by a fire started inside a screw type air compressor. It is likely that the compressor thermostatic valve failed to operate correctly. As a result, the temperature of the oil in the compressor increased until it reached its flashpoint. The oil was then ignited, probably by a hot spot within the compressor. Due to this accident two crew members experienced breathing difficulties. The helicopter evacuation was arranged, and the two affected crew members were taken to hospital for treatment and were discharged later that day. The above discussion clarifies that there is a need to address the proper maintenance planning on-board ships. The operations on-board ships at high seas are very complex in nature and are dependent on the competencies of the personnel operating and maintaining the machinery on-board. Moreover, the reliability of the system components has to be high. This will ensure high reliability of the subsystems, which in turn will ensure high reliability of the main propulsion engine (Monieta, 2016). Moreover, assessment of main engine failures done by various groups have shown that the failures of pistons, piston rings, cylinder liners and geometry of the combustion chamber are the highest percentage every year (Kamiski, 2017). Furthermore, research has been conducted to study the behaviour of the system components under various operational and maintenance policies. Therefore, it is necessary to evaluate an optimum maintenance plan which would ensure reliability of the main engine and at the same time be economically viable (Baliwangi et al., 2009).

In order to make better maintenance plans it is necessary to assess the reliability of the marine engines. However, there is a lack of appropriate data and model to fit the data. Therefore, collecting the relevant appropriate data is very important. Currently there are limited data available in the literature however, and it is not collected in a structured way to develop a reliability assessment technique. Moreover, most of the data are collected from studies with specific regional case studies. Therefore, in these studies, the lack of appropriate data is identified as a key knowledge gap. This knowledge gap limits the usability of any engineering approach to better understand and improve the reliability. The data collected in this study is through a questionnaire survey.

To meet the scientific rigour and enable generalization of the data and its interpretation, various sources of data and modes of feedback, such as interviews with experienced seafarers on-board, review of existing documentation, and a direct questionnaire method, can be used. The direct interview is generally conducted face to face. It offers a wide range of data some of which is unwanted (Patton, 2005; Stanton et al., 2013; Styśko-Kunkowska, 2014) and it is time-consuming. Furthermore, undesirable additional information may distract from the focus of the study and may be time consuming. Therefore, as noted by Witkin and Altschuld (1995) in many circumstances, respondents may be hesitant to put a number to a question, and the researchers may not come up with a result. Due to the respondent's hesitation to apply a number, the interview objective is affected which results in wastage of resources. Thus, direct interview has not been considered as a favourable option in the present study. Review of publicly available documentation is another option. However, appropriate reliable and comprehensive data for maintenance operations of marine systems are not publicly, nor widely, available. Therefore, this approach is not the most appropriate for the present study. The structured questionnaire method to acquire responses may be the most appropriate technique. It enables data collection from globally operating respondents. It widens the applicability of the method and helps to generalize the data and its interpretation. It is also an easy, effective, economical, flexible, and fast technique for data collection and development of a conceptual framework and has been previously used by researchers Attwood et al. (2006); Szolnoki and Hoffmann (2013) Islam et al. (2017); Islam et al. (2018). Therefore, this approach is adopted in this study.

This study aims to use the structured questionnaire to collect the relevant data for maintenance procedures of marine engines. The collected data will be extremely valuable for developing the reliability assessment techniques. Furthermore, this study will significantly help to fill the gap in conditional dependency of various components and subsystems of a main engine to develop advanced reliability assessment techniques such as Bayesian Network (BN). The responses provided in this study are collected from seafarers around the world and from the various types of marine engines, making the methodology more globally applicable for the reliability assessment.

The collected data is analysed through a series of statistical techniques to check the diversity and generalization of the data and its interpretation. Moreover, the collected relevant data from all the different sources is used to identify the most appropriate failure model representing specific components of a marine engine. This model will be very useful for a shipping company in planning their maintenance of the marine engine. This paper comprises six sections. Section 6.2 briefly presents the structure of the responses collected from the questionnaire, and Section 6.3 presents a selection of the respondents in conducting the survey. Section 6.4 presents a statistical analysis of the collected data. Section 6.5 presents the main finding of the study while Section 6.6 presents the conclusions.

6.2 Questionnaire Structure

The general structure of the questionnaire is discussed in this section to better understand the responses. The Main Engine is required to be associated with a number of subsystems to perform the task of propelling the huge merchant vessels (ABS, 2004). The key subsystems of a main engine are i) lubricating oil system ii) fuel oil system iii) cooling water system and iv) scavenge air system (Mollenhauer and Tschöke, 2010). The reliability of a marine engine is a product of the reliability of all the subsystems (i.e. lubricating oil system, fuel oil system, cooling water system and the scavenge air system). Therefore, the questionnaire in this study is structured in such a way that responses can be used to evaluate reliability of each subsystem and finally to assess the reliability of a main engine (Mokashi et al., 2002).

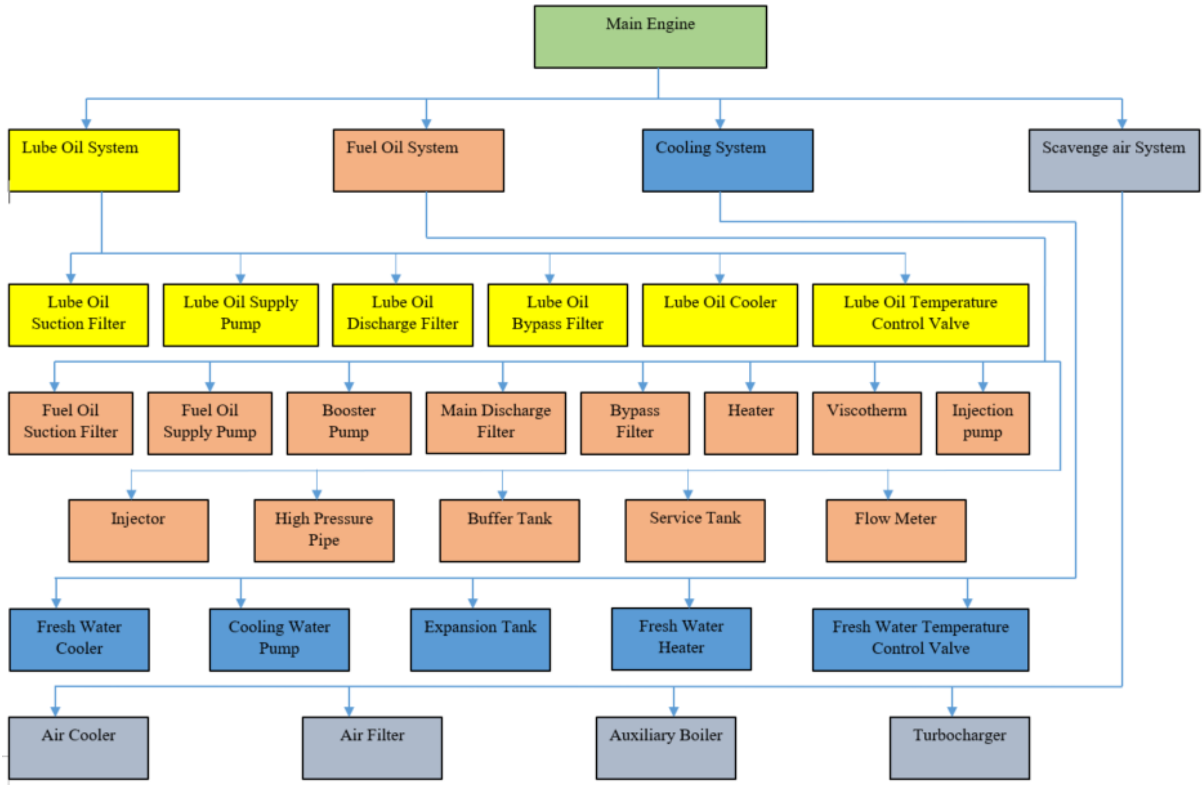


Figure 6.1: Structure of the Questionnaire

All the subsystems and components of the subsystem of a main engine are presented in Figure 6.1. These are the most important subsystems and components of a main engine. The questionnaire is developed to collect Failure Running Hours (FRH) data from experienced marine engineers. There are two questions in the questionnaire as presented in Table 1.

Table 1. Questionnaire to seek the feedback from experienced marine engineers

1. Please write the name of the engine and model number you have worked with (e.g. MAN B&W 6SMC60) in the box below.

2. Please provide Failure Running Hours (FRH) for the following component in the tables below. For example, if the Planned Maintenance Hours (PMH) is 500 and the component fails 100 hrs before PMH, it means (FRH) for the component is 400. Please note FRH < PMH.

Lube oil system						
	Lube oil suction filter	Lube oil pump	Lube oil main discharge filter	Bypass lube oil filter	Cooler	Lube oil temperature controller
FRH						

Cooling system					
	Expansion tank	Cooling water pump	Fresh water pump	Fresh water heater	Fresh water temperature controller
FRH					

Scavenge system				
	Turbo charger air filter	Turbocharger	Air cooler	Auxiliary blower
FRH				

Fuel oil system													
	Fuel oil suction filter	Fuel oil pump	Booster pump	Fuel oil main filter	Fuel oil by pass filter	Fuel oil heater	Viscotherm	Fuel oil injection pump	Fuel oil injector	Fuel oil high pressure pipe	Buffer tank	Service tank	Flowmeter
FRH													

Question 1 seeks a response to identify the type of engine and its model (e.g. MAN B&W 6SMC60).

Questions 2 seeks feedback to know the FRH for each individual components of a main engine's subsystems.

6.3 Selection of the Respondents

In order to complete the survey, a number of experienced marine engineers were identified in the shipping industry. The potential respondent selected was based on the following criteria: i) at least 5-10 years of engine maintenance experience on-board ship, ii) has been sailing as 3rd engineer, 2nd engineer or chief engineer for ship's engine department. A SurveyMonkey link was created in order to conduct the questionnaire survey. Ethics approval was sought, as per the guidelines of the University of Tasmania. Therefore, a human research ethics approval was obtained from the University of Tasmania's human research ethics committee (Ethics Ref No: H0014474). The SurveyMonkey link was sent around the world by email to a total of 200 experienced ship's engineers, and of 101 responses were received . In other words, the response rates are 50.5%. Responses to these questions were analysed to qualify the subjectivity and uncertainty in the responses. To statistically validate the accuracy of the collected responses, the required sample size is estimated using Equation 1.

Required responses $n = \frac{Z^2 \; P(1-P)}{e^2}$ (1)

Where e is the margin of error (e = ± 0.10); Z is normal scale value corresponding to 95% confidence. P is the level of satisfaction considered to have the median value of 0.50. Results of the required sample size demonstrate that it is necessary to have 96 responses from the engineers to statistically justify the accuracy of the collected response. The responses reported in this study are more than the required number of responses. This confirms the validity of sufficient responses and assumption of normality distribution of responses.

6.4 Statistical analysis of the data

Statistical analysis is the science of collecting, examining, interpreting and presenting data to determine the basic form, relationships, and trends. Statistical analysis for research is necessary as it offers clarification of several concepts, theories, frameworks and methods. Moreover, it helps in arriving at conclusions and providing the hypothesis. Therefore, after collecting the data, the FRH was computed and statistical analysis was carried out. After collecting the data, a box plot of the data set was drawn in order to eliminate the outliers. A box plot is a method for representing statistical data on a plot to visualize key statistical measures. The box plot was drawn for all the components of a sub-systems individually and the outliers were removed. The drop box plot for one of the subsystems is provided in Figure 6.2 below.

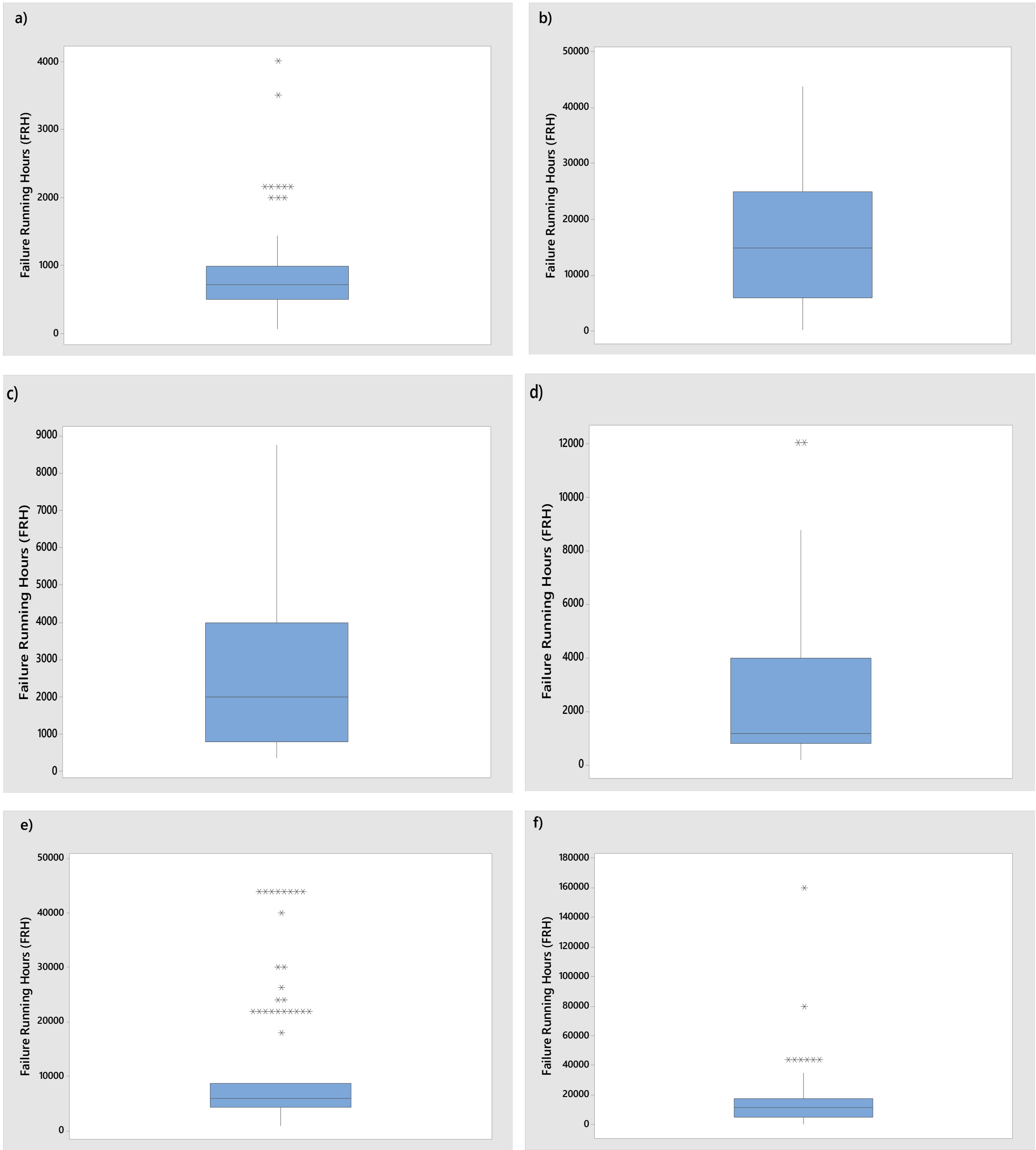


Figure 6.2: Box plot of Lubricating Oil System: a) Lube Oil Suction Filter, b) Lube Oil Pump, c) Lube Oil Discharge Filter, d) Lube Oil Bypass Filter, e) Lube Oil Cooler, f) Lube Oil Temperature Control Valve.

The outliers were removed from the data set considering 95% confidence interval. The filtered data is then presented for all the components of various subsystems of a main engine in Figures 6.3 to Figure 6.6. The data is presented in a frequency plot rather than a normal line graph. This frequency plot provides a clear understanding of what the data looks like.

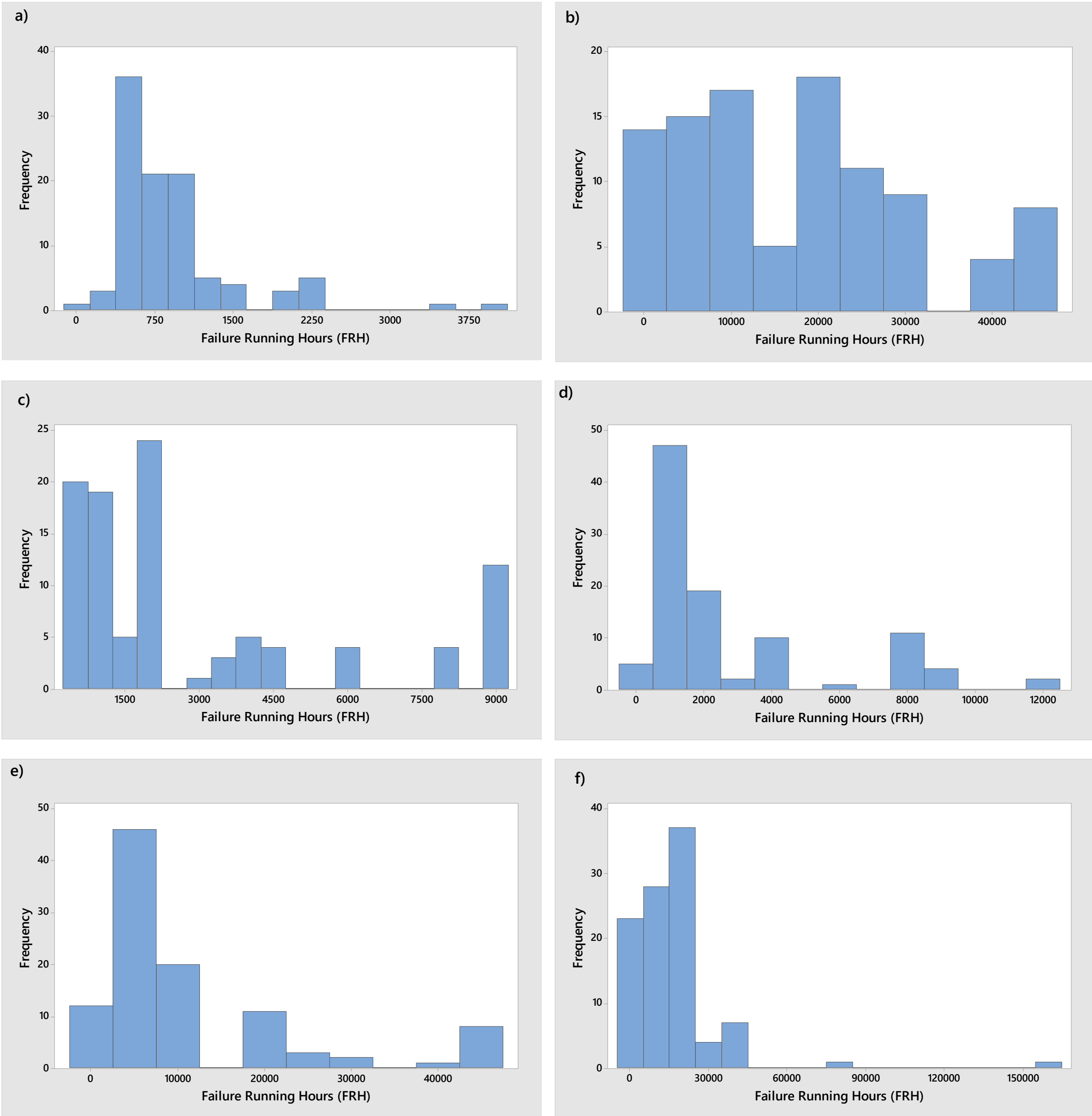
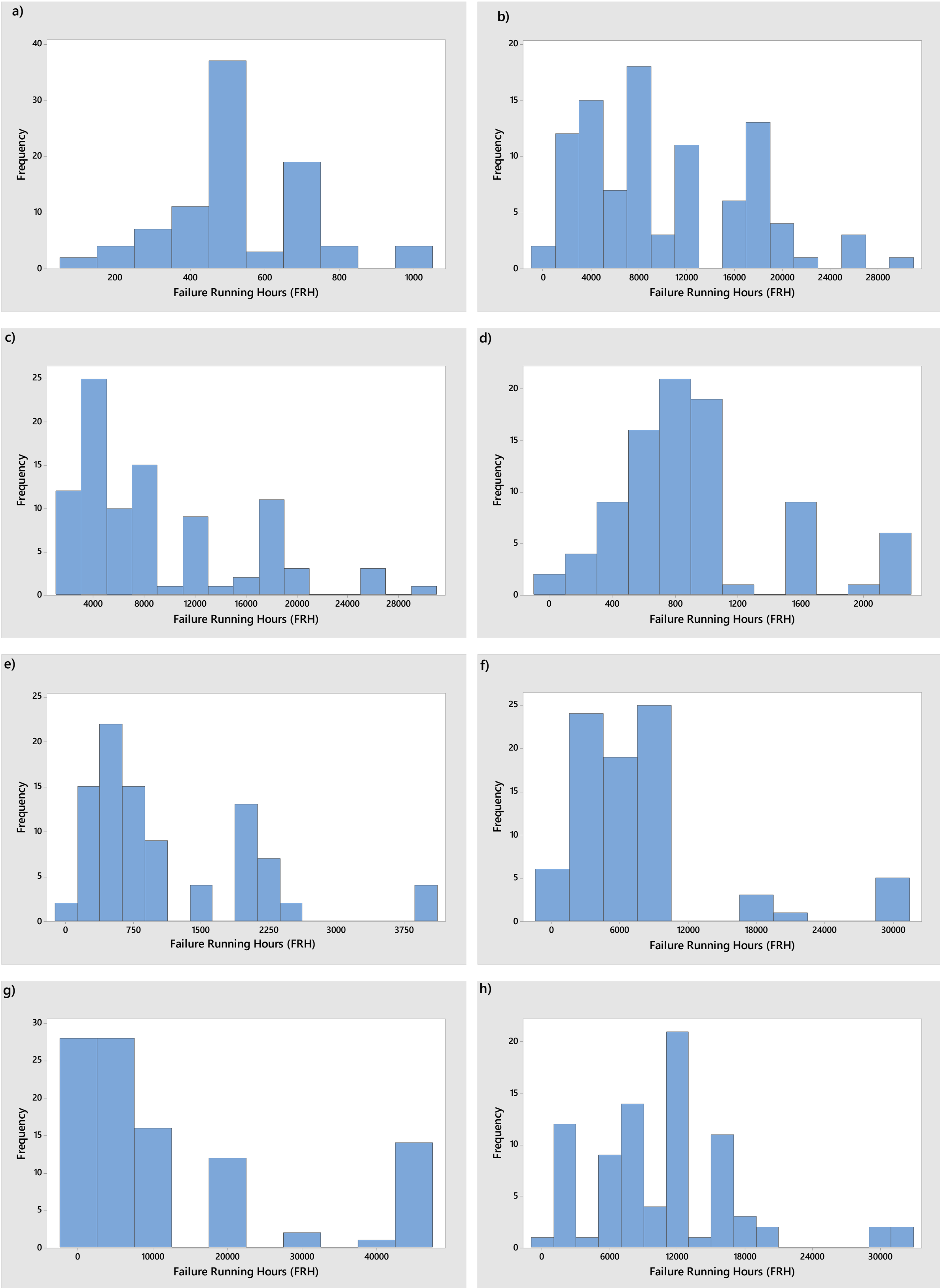


Figure 6.3: Frequency plot of Lubricating Oil System: a) Lube Oil Suction Filter, b) Lube Oil Pump, c) Lube Oil Discharge Filter, d) Lube Oil Bypass Filter, e) Lube Oil Cooler, f) Lube Oil Temperature Control Valve.


a)
Frequency
0
10
20
30
40
200
400
600
800
1000
Failure Running Hours (FRH)
b)
Frequency
0
5
10
15
20
0
4000
8000
12000
16000
20000
24000
28000
Failure Running Hours (FRH)
c)
Frequency
0
5
10
15
20
25
4000
8000
12000
16000
20000
24000
28000
Failure Running Hours (FRH)
d)
Frequency
0
5
10
15
20
0
400
800
1200
1600
2000
Failure Running Hours (FRH)
e)
Frequency
0
5
10
15
20
25
0
750
1500
2250
3000
3750
Failure Running Hours (FRH)
f)
Frequency
0
5
10
15
20
25
0
6000
12000
18000
24000
30000
Failure Running Hours (FRH)
g)
Frequency
0
5
10
15
20
25
30
0
10000
20000
30000
40000
Failure Running Hours (FRH)
h)
Frequency
0
5
10
15
20
0
6000
12000
18000
24000
30000
Failure Running Hours (FRH)

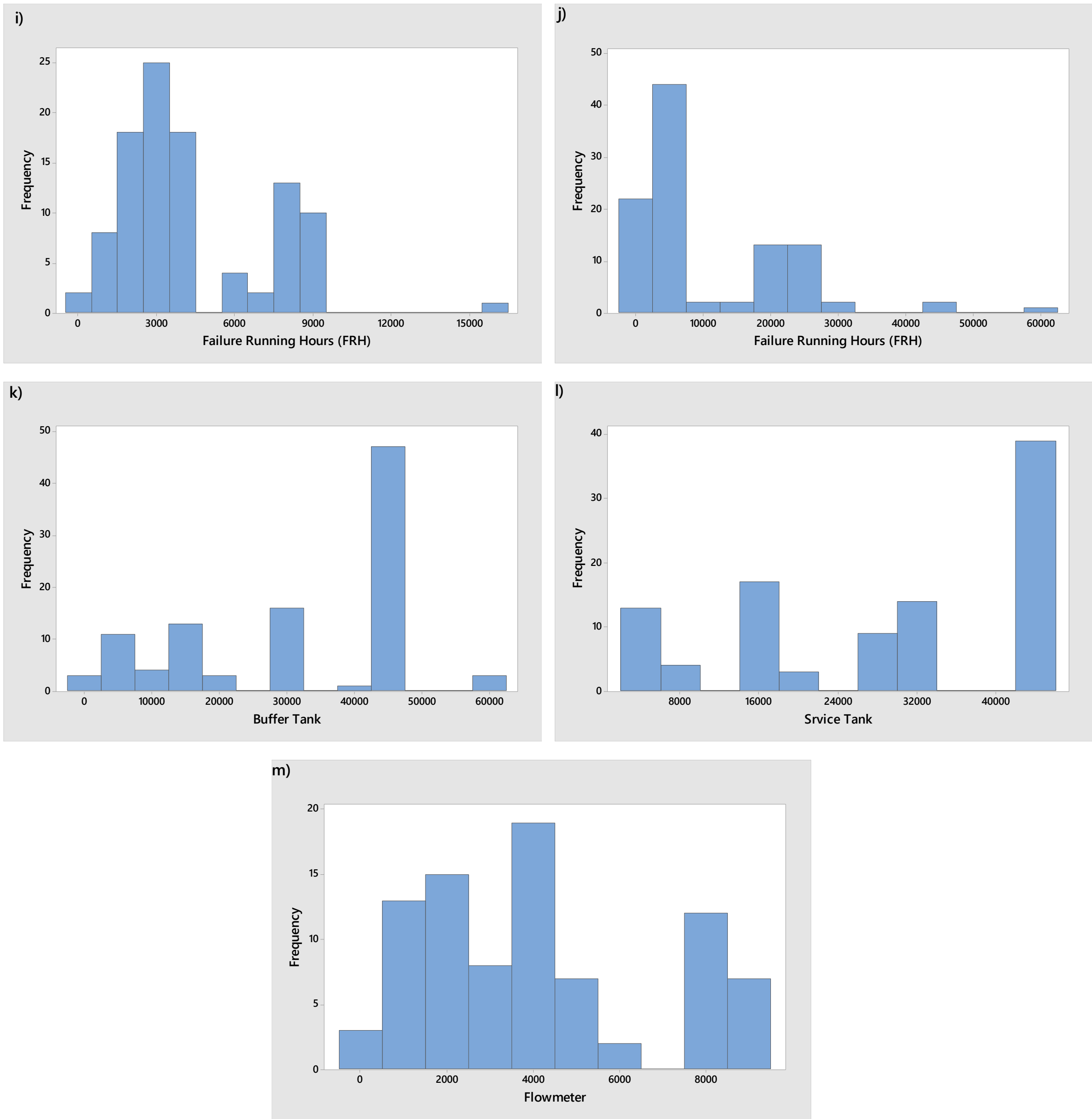


Figure 6.4: Frequency plot of Fuel Oil System: a) Fuel Oil Suction Filter, b) Fuel Oil Supply Pump, (c) Booster Pump, (d) Fuel Oil Main Discharge Filter, (e) Fuel Oil Bypass Filter, (f) Fuel Oil Heater, g) Viscotherm, h) Fuel Oil Injection Pump, i) Fuel Oil Injector, j) Fuel Oil High Pressure Pipe, k) Buffer Tank, l) Service Tank, m) Flow Meter.

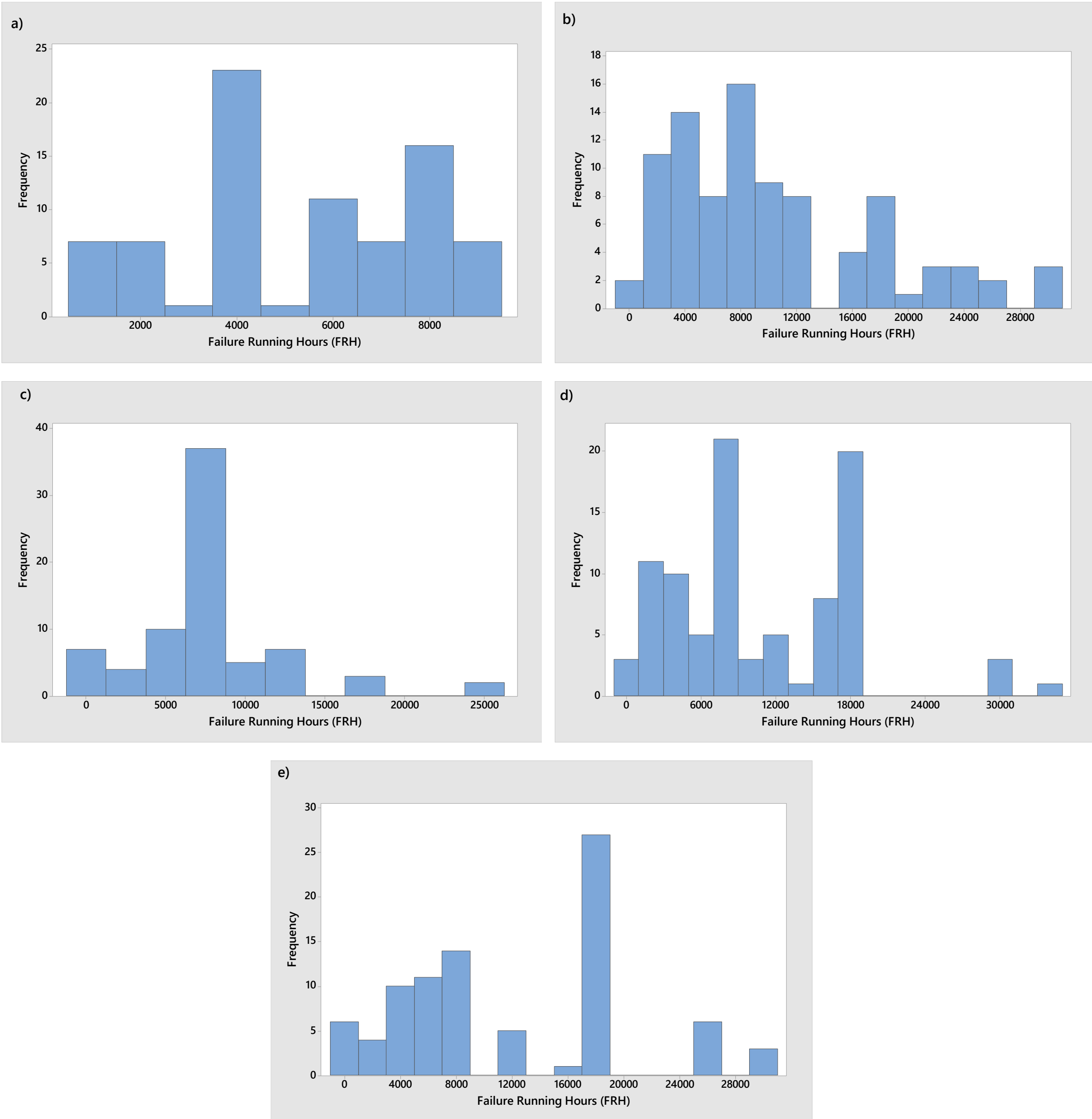


Figure 6.5: Frequency plot of Cooling Water System: a) Fresh Water Cooler, (b) Cooling Water Pump, (c) Expansion Tank, (d) Fresh Water Heater, (e) Fresh Water Temperature Control Valve.

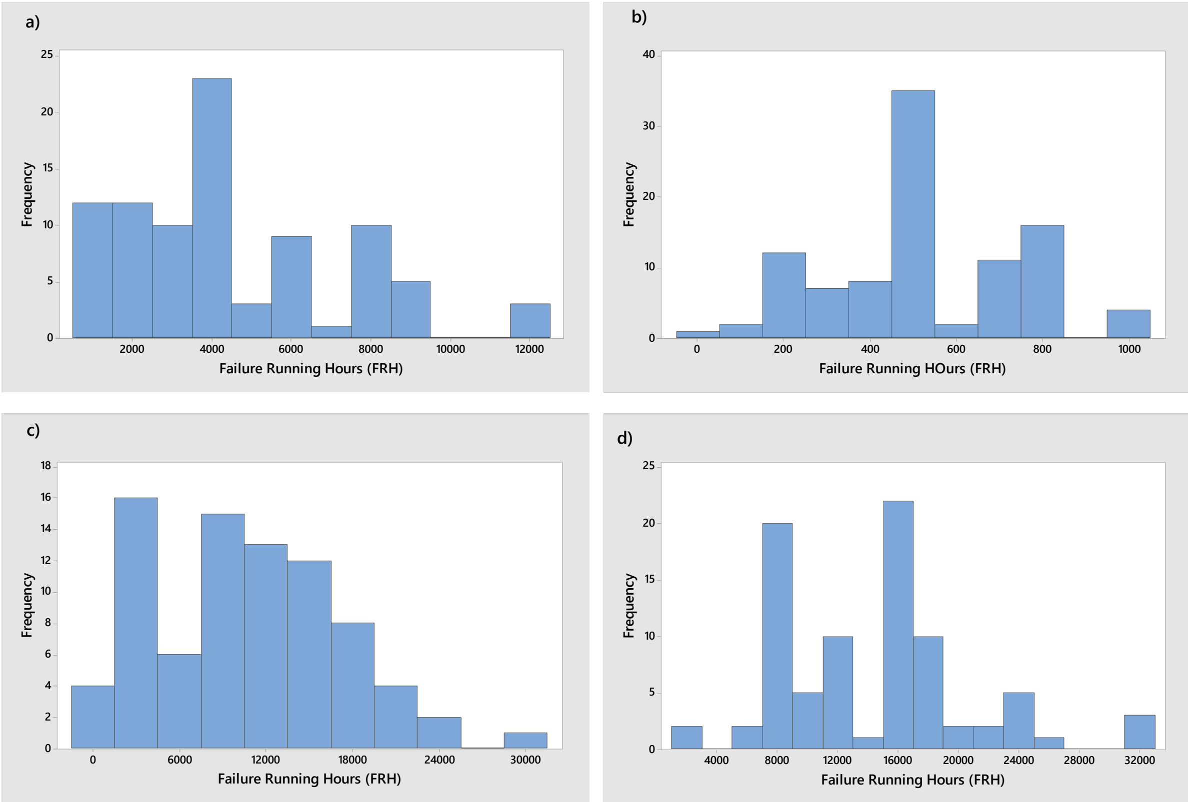


Figure 6.6: Frequency plot of Scavenge Air System: a) Air Cooler, b) Turbocharger Air Filter, (c) Auxiliary Blower, d) Turbocharger.

The authors assumed the collected data is not from a normal distribution and have not performed a normality test and therefore directly drew the Weibull plot in order to identify the distribution of the dataset. The Weibull plot is a graphical technique for determining whether the data set came from a population that would logically fit with a Weibull distribution. The Weibull plot is drawn for all the components and subsystems of a main engine. The Weibull plot for one of the data sets is presented in Figure 6.7. Based on the plot p value is <0.05. Hence, it can be concluded that the data set does not follow the normal distribution. In this study the Weibull plot is drawn using Minitab 18 statistical software. Moreover, the Weibull plot shows that the data set does not come from a population that would fit a Weibull distribution.

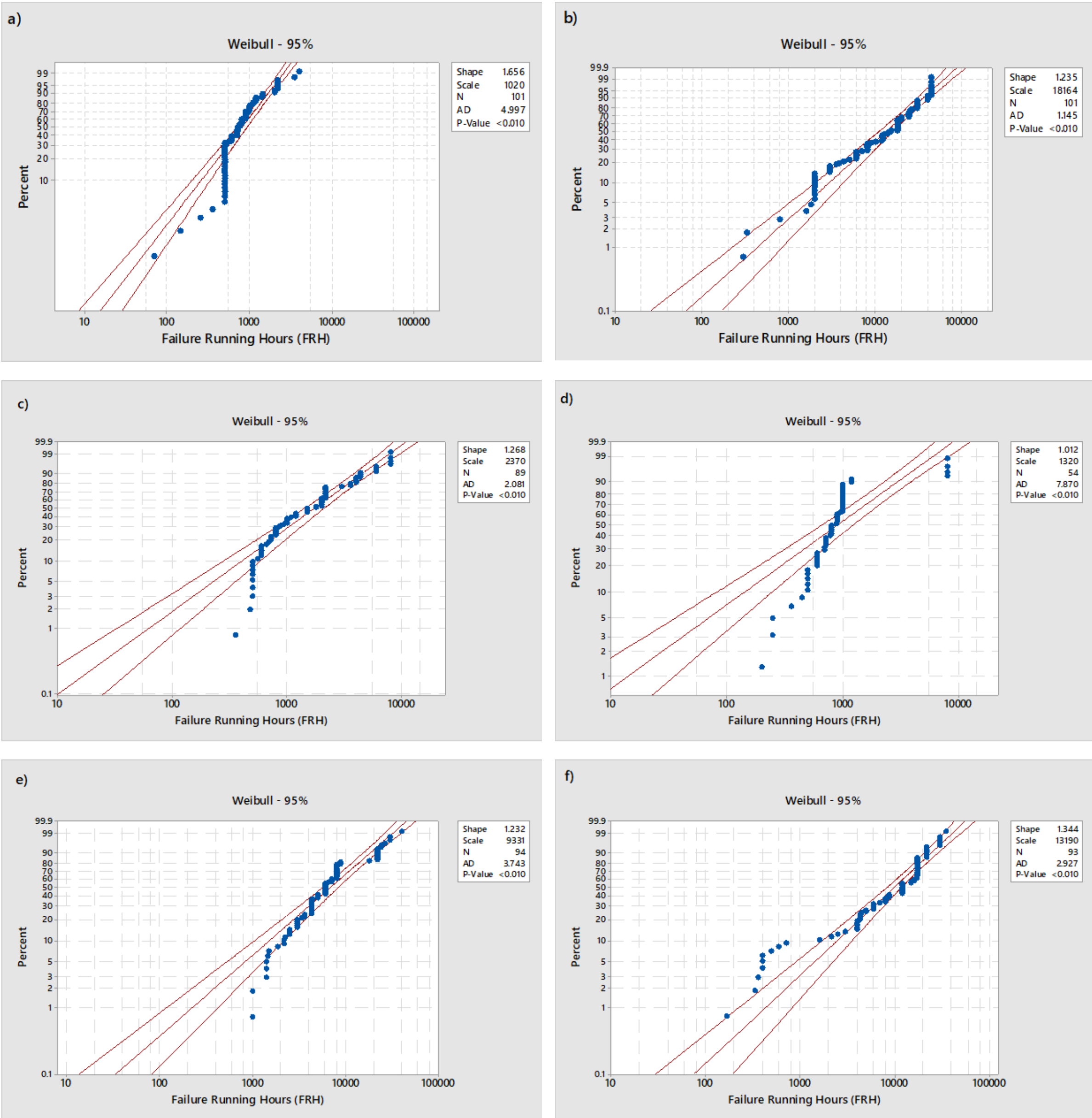


Figure 6.7: Weibull plot of Lubricating Oil System: a) Lube Oil Suction Filter, b) Lube Oil Pump, c) Lube Oil Discharge Filter, d) Lube Oil Bypass Filter, e) Lube Oil Cooler, f) Lube Oil Temperature Control Valve.

The Weibull plot in Figure 6.7 demonstrates that the data does not follow Weibull distribution. As the data points are not in good agreement (not following the straight line) with the fitted distribution line in Weibull distributions. Therefore, in order to identify the best fit of the data it is required to goodness of fit test. The probability plot based on Anderson-Darling approach is used in order to identify the best fit of the data. Probability plot of one of the sub-systems is presented in Figures 6.8. to 6.13.

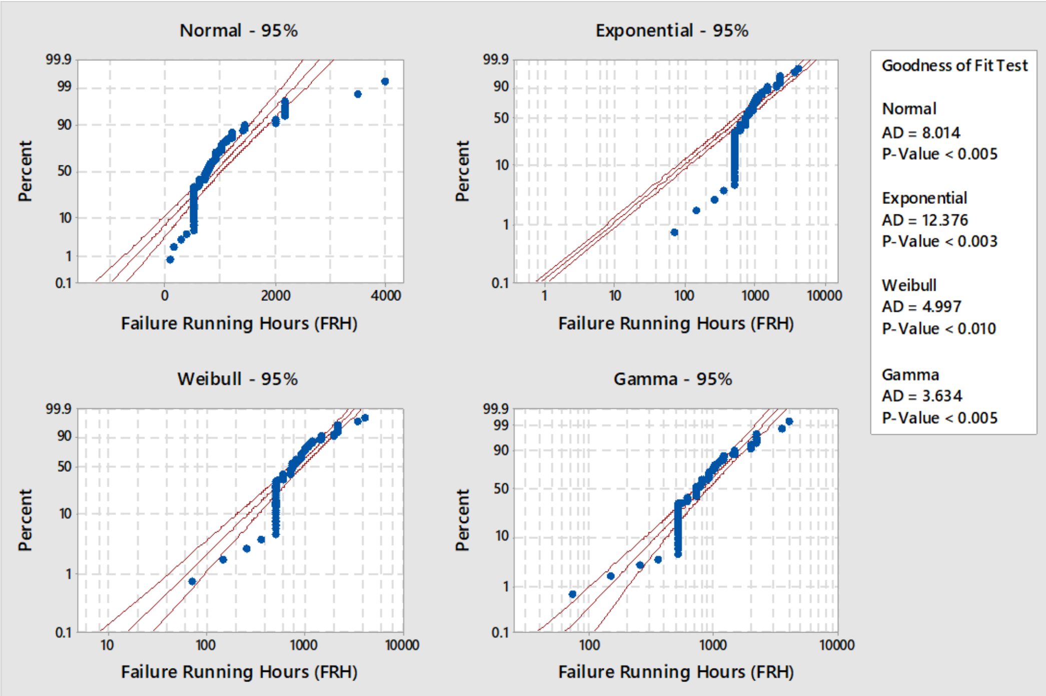


Figure 6.8: Probability Plot based Anderson-Darling approach to identify the best fit distribution for the Lube Oil Suction Filter

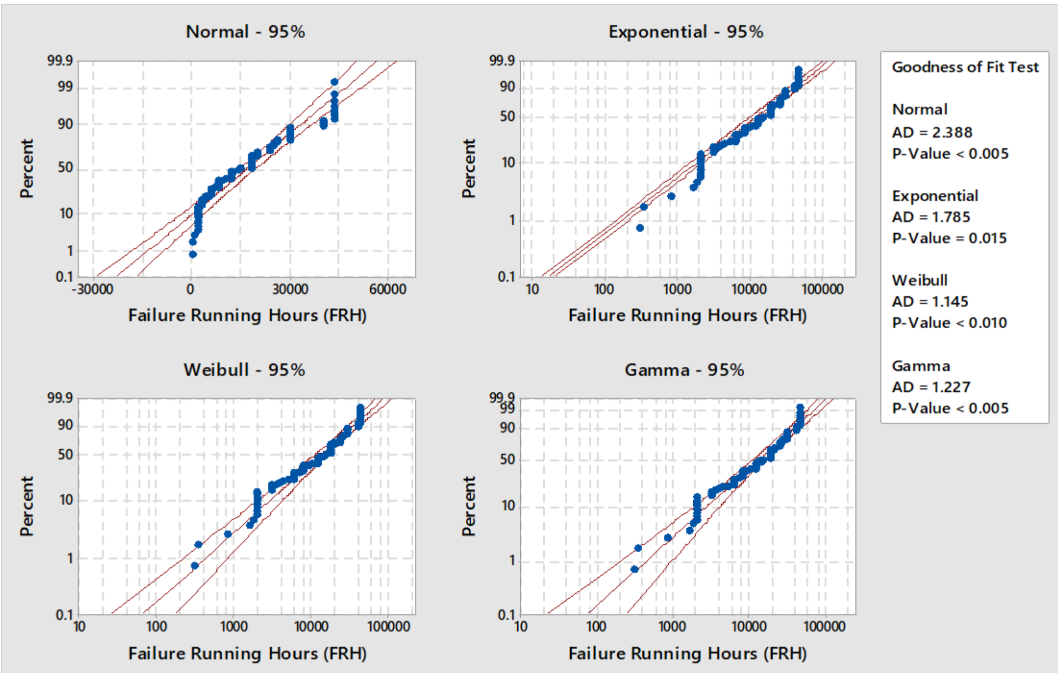


Figure 6.9: Probability Plot based Anderson-Darling approach to identify the best distribution for the Lube Oil Pump

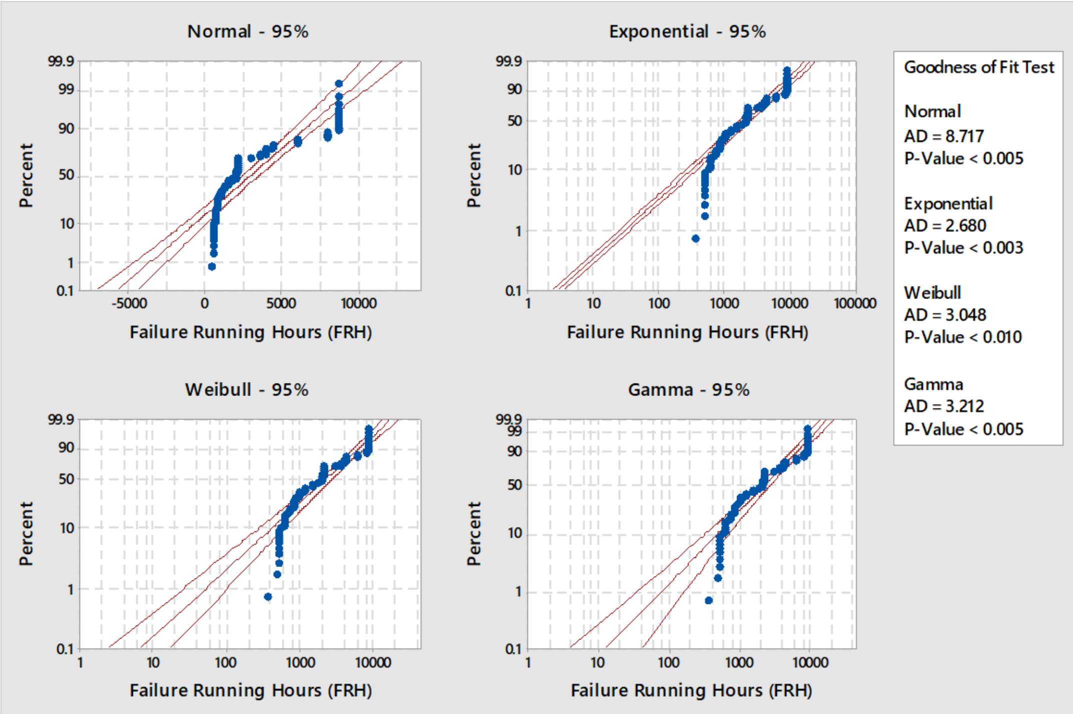


Figure 6.10: Probability Plot based Anderson-Darling approach to identify the best fit distribution for the Lube Oil Discharge Filter

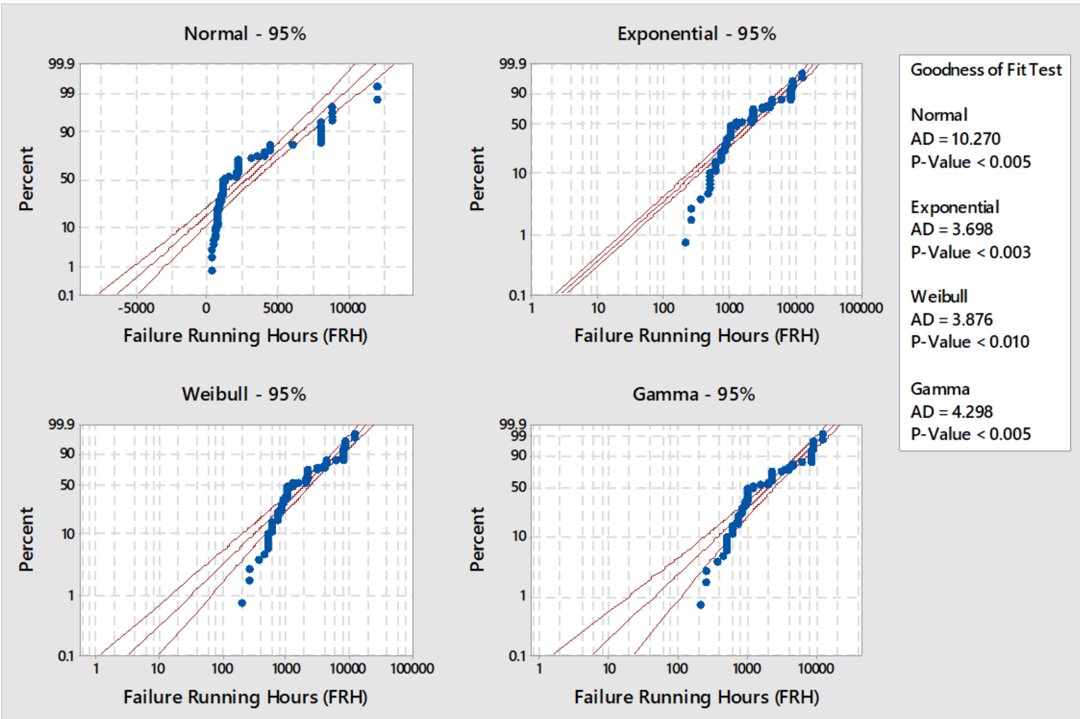


Figure 6.11: Probability Plot based Anderson-Darling approach to identify the best fit distribution for the Lube Oil Bypass Filter

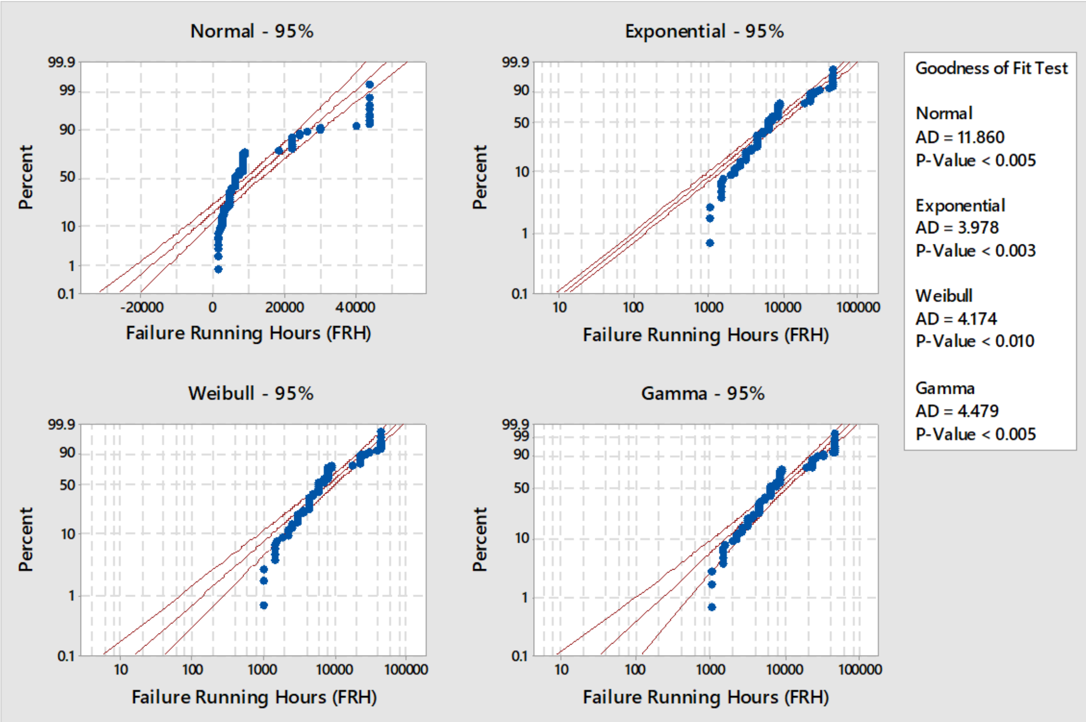


Figure 6.12: Probability Plot based Anderson-Darling approach to identify the best fit distribution for the Lube Oil Cooler

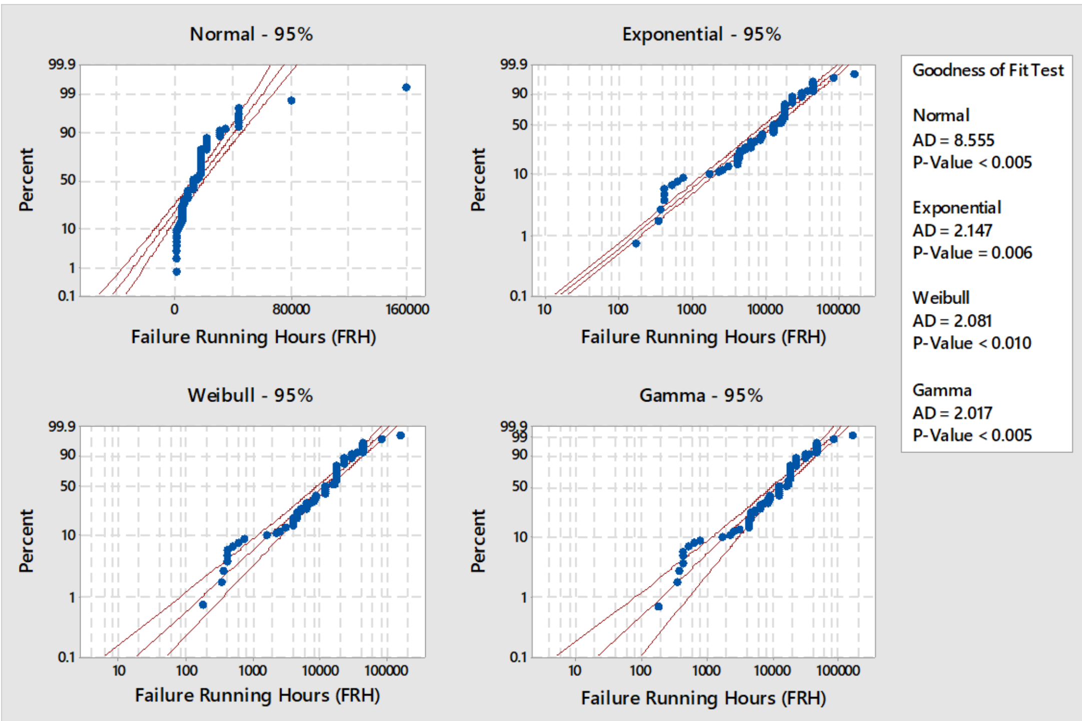


Figure 6.13: Probability Plot based Anderson-Darling approach to identify the best fit distribution for the Lube Oil Cooler temperature control valve

Based on the plots in Figures 6.8 to 6.13, it is very difficult to identify the best fit visually. Therefore, it is necessary to look at the Anderson-Darling statistics to identify the best fit. Anderson-Darling statistics is a measure of how far the plot points fall from the fitted line in a probability plot. The statistics are a weighted squared distance from the plot points to the fitted line with larger weights in the tails of the distribution. Probability Plot based on the Anderson-Darling approach is conducted using statistical software Minitab 18. Minitab uses an adjusted Anderson-Darling statistic, because the statistic changes when a different plot point method is used. A smaller Anderson-Darling statistic indicates that the distribution fits the data better. It can be seen from the plot that not all the data followed same distribution. Data set for the various components of the subsystems has a different best fit. For example, components of a lube oil systems, suction filter, control valve has gamma distribution as a best fit. However, lube oil pump has a Weibull distribution as a best fit. Moreover, discharge filter, bypass filter and cooler have an exponential as a best fit of the distribution. As most of the data set followed the exponential distribution, the exponential distribution is identified as a best fit of a data set in this study.

6.5 Results and Discussion

The results of the lubricating oil system components are presented in Figure 6.14, It is observed that the Lube oil suction filter, discharge filter and bypass filter have a lower failure running hours (FRH), whereas the components such as pump and temperature control valve have a higher failure running hours (FRH) and the lube oil cooler has a moderate failure running hours (FRH).

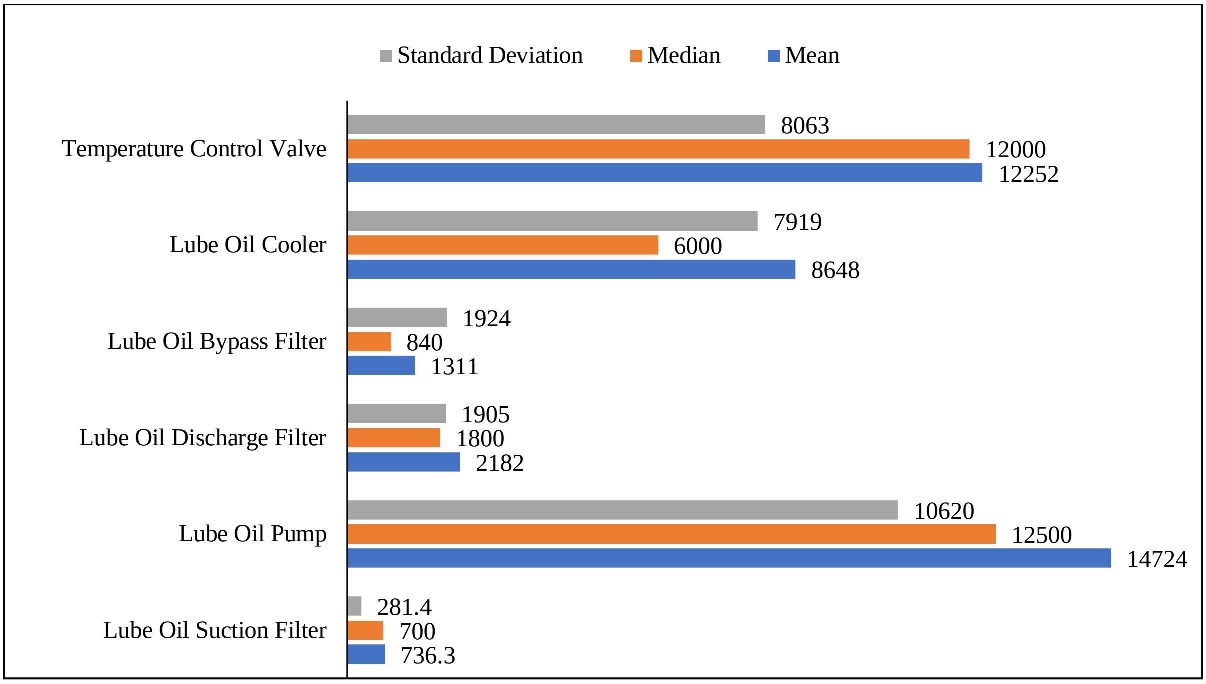


Figure 6.14: Failure Running Hours (FRH): Mean, Median and Standard Deviation of Lubricating Oil System

Marine Engineers have the responsibility of ensuring smooth operation, running and maintenance of the vessel. The system layout and system redundancies is beyond the scope of an operating Marine Engineer or Chief Engineer. The data analysis leads to the fact that the maintenance of the filters is a highly critical aspect of the main lubricating oil system, (Knowles and Baglee, 2012). Most systems on board a vessel have a redundancy with two suction filters in the line, one in use and the other on standby. Clogging of filters in normal operation may be due to incorrect purification of the lube oil system or carry over of debris due to normal wear and tear of the bearings. Clogging of filters may also be related to rough weather conditions, where heavy rolling and pitching may cause inadvertent clogging of the filters. Consideration could be given to installation of an additional suction filter which could be useful in rough weather conditions. The lubricating oil pumps are normally well-designed screw pumps used to handle the system lube oil. It can be seen that the failure running hours (FRH) for the pump are reasonably high, hence overhauling of the same could take place once in two years or during the drydock of the vessel. The cooler has a moderate failure running hours (FRH), hence an annual cleaning of the cooler could be considered, but keeping in mind that the pressure drops across the cooler and high lube oil outlet temperature.

The results of the fuel oil system components are presented in Figure 6.15. Failure Running Hours (FRH) for filters in the line are low ranging between 528.5 to 1,122.5 hours. Failure Running Hours (FRH) for fuel oil supply pumps, fuel oil booster pumps, viscotherm, fuel oil heater, fuel injection pump and fuel injectors are relatively moderate, values ranging between 7,420 to 10,149 hours. Failure Running Hours (FRH) for fuel oil service tank and buffer tanks are high at around 30,000 hours mark.

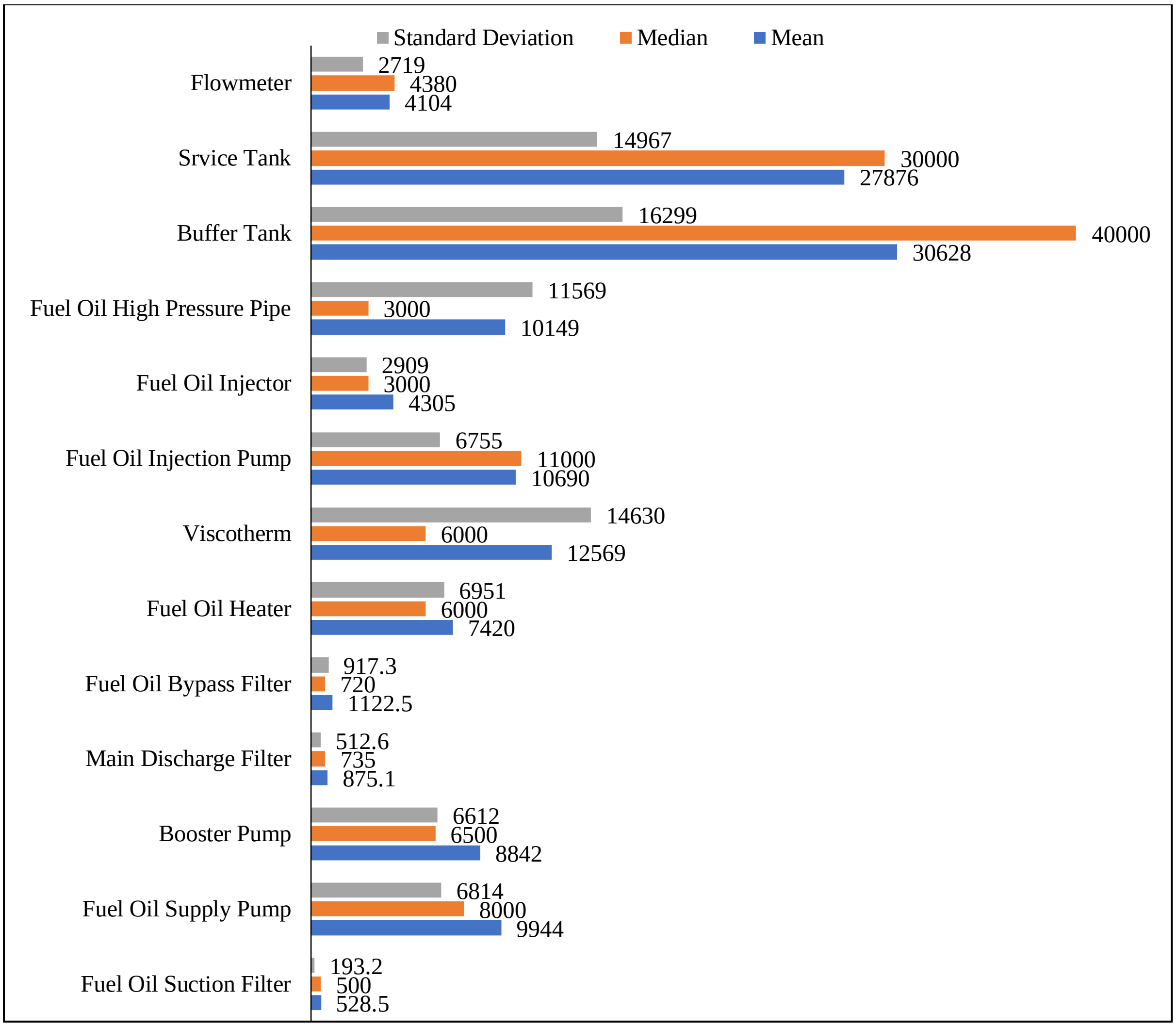


Figure 6.15: Failure Running Hours (FRH): Mean, Median and Standard Deviation of Fuel Oil System.

The Fuel Oil Service tank and Buffer tank form part of the system but they are static components with no dynamic loading. They require minimum maintenance. Service tanks need to be maintained at the correct temperature and the bottom of the tank requires to be drained periodically of sludge and water. Fuel oil filters need to be carefully looked at and periodically cleaned at the required maintenance interval. Parameters such as pressure drop across the filter should be useful to ascertain the condition of the filter. From the analysis it could reasonably be concluded that these filters need to be attended to at least every 500 hours of the engine running. Other components of the fuel oil system include fuel injection pump and fuel injectors which have a moderately high Failure Running Hours (FRH), (Cicek et al., 2010). The condition of these components could be ascertained by doing an overall engine performance check. These components form a vital part of the main engine. Manufacturers specified intervals should be a good guideline to avoid failure of these components on a running engine. The results of the cooling water system components are presented in Figure 6.16.

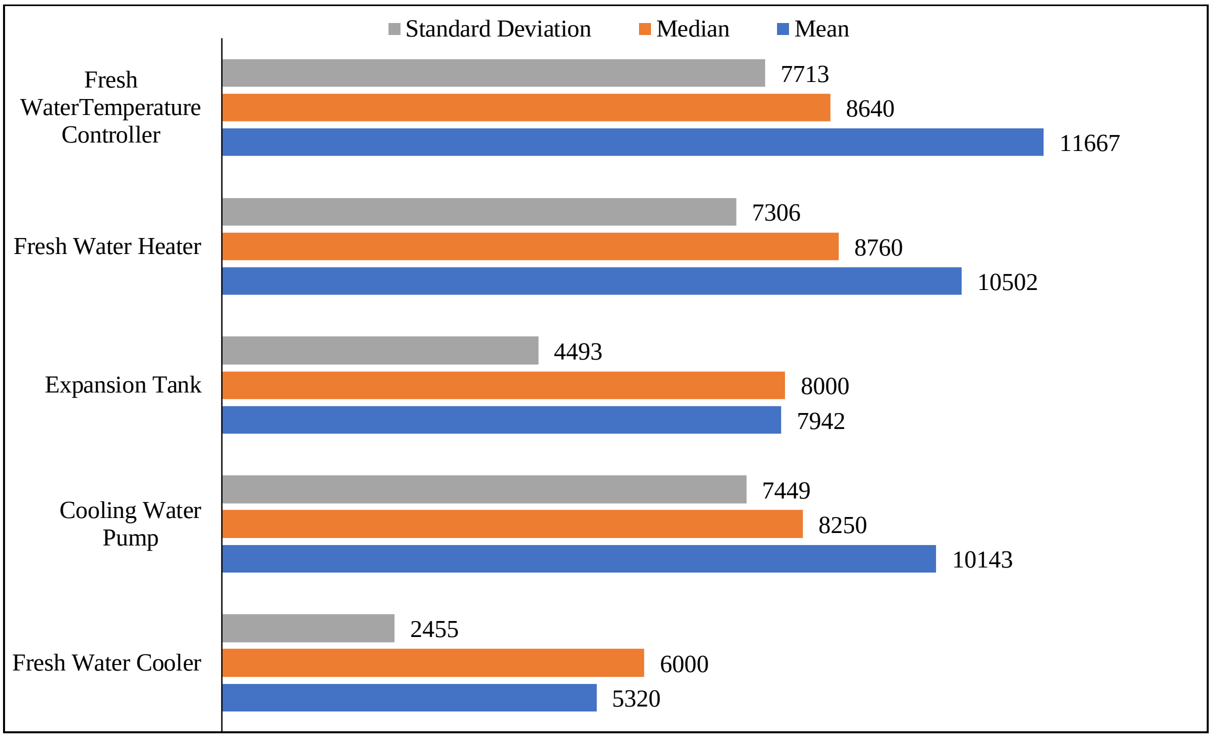


Figure 6.16: Failure Running Hours (FRH): Mean, Median and Standard Deviation of Cooling Water System.

Failure Running Hours for the fresh water cooler is around 600 hours which is the minimum. The Expansion tank has a moderate Failure Running Hours (FRH) around 8,000 hours. Cooling water pump, fresh water heater and temperature control valve have a relatively high Failure Running Hours (FRH) of more than 10,000 hours. Expansion tank is a stationary component not subjected to any dynamic load, hence we should expect a high Failure Running Hours (FRH). Fresh water cooler functions to cool the engine fresh water by sea water. Modern vessels are installed with plate type fresh water coolers which are highly efficient, hence we could expect a relatively high Failure Running Hours (FRH). The differential temperature between the sea water inlet and outlet should be a good guide to carry out cleaning of the cooler. Fresh water pumps are of the centrifugal type, with one pump in operation and another on standby. These pumps ae changed over to perform duties every alternate voyage. Moreover, the fresh water in the engine jacket cooling system is chemically treated to inhibit corrosion of the components (Bocchetti et al., 2009), (Lee et al., 2017). Cooling water treatment of the cooling water system goes a long way in dictating the life of the cooling water system components. The results of the scavenge air system components are presented in Figure 6.17.

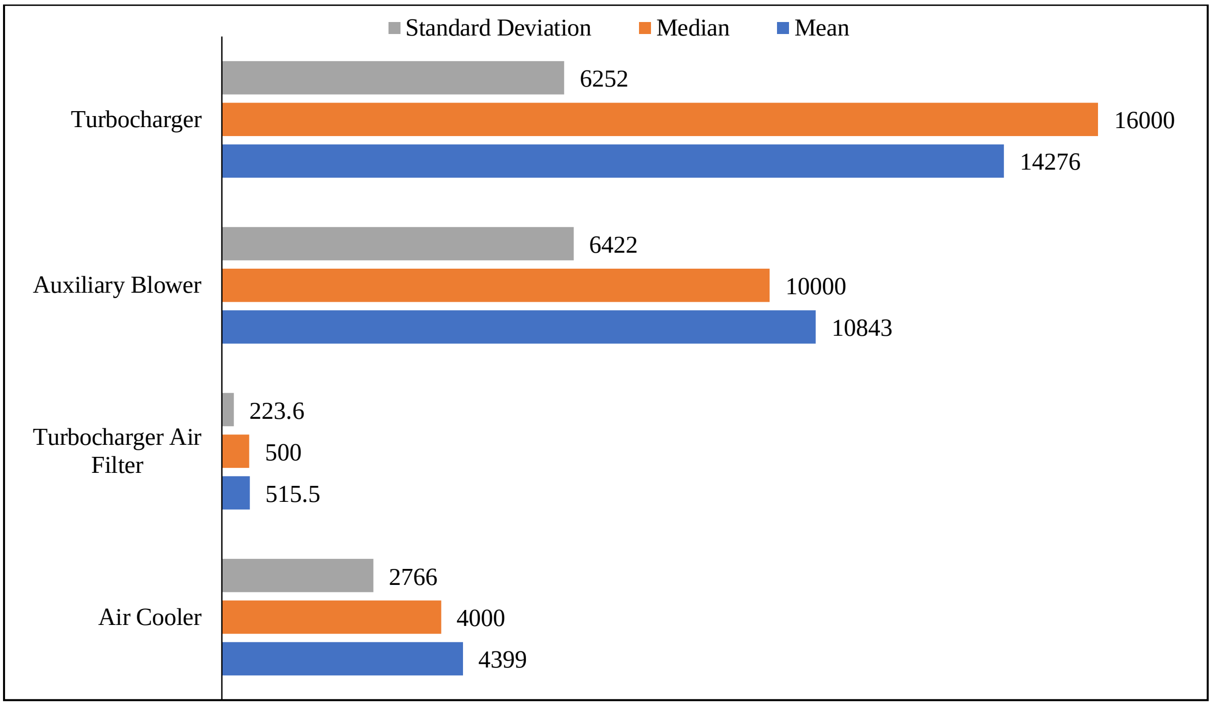


Figure 6.17: Failure Running Hours (FRH): Mean, Median and Standard Deviation of Scavenge Air System

Data analysis of the scavenge system reveals that the turbocharger air inlet filter has a low Failure Running Hours (FRH), followed by a moderate Failure Running hours (FRH) for the air cooler and finally a high Failure Running Hours (FRH) for the Auxiliary blower and the turbocharger. The engine room atmosphere, which is generally oily and misty is responsible for the condition of the turbocharger air inlet filters. In addition when the vessel arrives in port, it is to be ensured that the filter elements are well covered and protected, especially in a port where bulk cargo such as coal, iron ore or grain is being loaded. If the filter casing is not protected by the dedicated cover, it is likely that the filters become clogged, causing a huge problem during departure of the vessel from the port of discharge. Hence it is prudent to keep this filter clean at all times. The pressure drop across the filter should not exceed 50 mm water gauge. The air cooler is a very vital part of the scavenge system and the main engine in general. An efficient cooler plays a prominent part in efficient running of the engine. The air discharged from the turbocharger needs to be cooled by the air cooler and then discharged to the scavenge air trunking temperature being around 40 – 45 degrees Celsius. The cooling medium is normally sea water. The pressure drop across the air cooler is an important parameter which helps us to determine the condition of the air cooler, preferred value being 100 to 150 mm maximum value. Modern engines are equipped with a cleaning in place (CIP) system for the air cooler, which has made maintenance very easy. This should be reliably done after a long voyage. The Auxiliary Blower is run during manoeuvring and during emergency. It has low running hours, hence the Failure Running Hours (FRH), could be expected to be high. The Turbocharger is a very vital component which serves to keep the efficiency of the engine high (Banisoleiman and Rattenbury, 2006). Modern turbochargers are designed to a provide a highly efficient scavenging system. There are many planned maintenance tasks which are carried out, which keeps the turbocharger in very good running condition. Failure Running Hours (FRH) is relatively high. Turbochargers can fail for various reasons with disastrous consequences. Additionally, engine issues may cause turbocharger failures, scavenge fire being one such condition which could lead to a turbocharger failure.

The authors introduced a new concept of FRH which is termed as the failure running hours. It is necessary to look at data from vessels where failure of the components has occurred after the component in question is overhauled or replaced by a new one. In case of non-failure of the component, it would be assumed that there is a likelihood that the component in question will fail at the recommended PMS hours, in case where no action is taken. Some important observations from the failure running hours (FRH) of the various components revealed some interesting results. Components such as suction filters and discharge filters in the main engine lube oil and fuel oil system showed low FRH, whereas other system components like pumps, coolers and heaters had high FRH.

Components like suction and discharge filters had redundancies and low FRH, whereas some components like line heaters and coolers had no redundancies, yet displayed comparatively higher FRH. Components like pumps had redundancies and displayed higher FRH. Suction filters are the first component in the lube oil, fuel oil or scavenge systems, hence they are subject to the most hazardous operating conditions. Failure of the filters brings the system to a halt. Additional redundancies may be provided to certain components like suction filters. This may ensure a higher system reliability.

6.6 Conclusions

This study represents useful data for the reliability analysis of a marine engine. The collected data is unique in this field of study. The large set of collected data enables generalization and processed data will help to develop reliability analysis techniques. The subjectivity and variability of the collected data are analysed and identified as less than 10%, therefore. providing a higher confidence in the data and its generalization. The analysis of the data collected through a structural survey demonstrates the significance of a marine engine subsystems and its components during the voyage. The collected relevant data from all the numerous sources is used to identify the most appropriate failure model representing specific components of a marine engine. The results of this study indicate that not all the data for a component of a marine engine subsystem follows the same behaviour. However, most of the components follow the exponential distribution. Therefore, it is concluded that time between failure events model, which is exponential distribution, is the best fit for the collected data. This model will be very useful for a shipping company for planning their maintenance on the voyage and the ship. The shipping company now have a starting point and can begin to revise the model based on the data from their own ships.

7. Conclusions

The main theme of this research was to develop tools to plan and maintain the main engine at its best performance when propelling a vessel in high seas in any hazardous environment. To achieve this theme, it was necessary to consider a multidisciplinary approach.

One of the main factors leading to a reliable main engine is to ensure high reliability of the subsystems of the main engine. Another factor which plays a dominant part in reliability of the main engine is the maintenance regime of the main engine.

7.1 Maintenance regime for the main propulsion engine.

Case studies for a vessel's engineering system were considered and analysed. In addition, the maintenance regime of sister transport industries such as railways, airlines and other allied industries such as oil and gas and chemical industries, which had operating equipment similar to a vessels' operating equipment was studied. It was concluded that the present established practice of following a Planned Maintenance System (PMS) regime on board vessels could lead to machinery failure, resulting in stoppage of a vessel at sea at a critical juncture (M. Anantharaman & Lawrence, 2013). Further it was concluded that for merchant shipping to be safe and reliable, it is extremely important that efforts be made to change from PMS to CBM (Condition Based Maintenance). The main propulsion engine of a vessel should be the focal point of CBM and it can be worked around the related subsystems. Fault Tree Analysis (FTA) is a good approach wherein the basic event can be identified, failure of which could lead to a possible catastrophic failure of the main engine. It was concluded that FTA be used in conjunction with Reliability block diagrams (RBD) for effective statistical analysis (MP Anantharaman, 2002, 2003).

7.2 Reliability of subsystems of the Main Engine

Main Engine lubricating oil system, which is a vital part of the main propulsion system was analysed. Failure of the main engine lubricating system may result in serious damage to engine components and failure of the main engine at sea. A step by step approach for evaluating the reliability of the main engine lube oil system was undertaken. From the evaluation it was concluded that use of additional components in the system, could provide improvement in the component reliability and contribute to overall reliability of the Main Engine lubricating oil system (Anantharaman et al, 2014).

The second critical subsystem analysed was the main engine fuel oil system. A step by step approach for evaluating the reliability of the main engine fuel oil system is presented. It was concluded that utilizing the least failure rate of the fuel oil system component, as an identical value of failure rate for all components in the fuel oil system, the overall reliability of the main engine fuel oil system, could then be improved considerably (Anantharaman, et al, 2015).

7.3 Impact of recent developments in marine engines on reliability

From the studies undertaken it was concluded that large slow speed diesel engines will continue to dominate the propulsion of giant size vessels. With gruelling bunker fuel costs, one needs to be cautious in running these vessels economically, and efficiently while simultaneously protecting the marine environment. Engine manufacturers are continuously working on research and development, but further improvement in specific fuel oil consumption does not appear to be on the cards in the very near future. However, slow steaming of vessels especially mega container vessels is seen as a considerable means in reducing fuel consumption. Electronically controlled engines offer great precision in terms of fuel injection and exhaust emission controls. Development of turbochargers will play a major role in complementing and improving the overall efficiency and reliability of the main engine (Anantharaman, et al, 2015).

7.4 Hybrid model for quantification of reliability

Various models were considered to quantify the reliability of the main engine. A hybrid method was employed to determine the combined reliability of three subsystems of a vessel's main engine which includes the fuel oil system, lubricating oil system and the scavenge air system. The fuel oil and lubricating oil system were modelled by Markov analysis and the scavenge air system was analysed using Weibull distribution which is a time dependent failure model. A hybrid model is presented to make reliability assessment of vessel's main engine by combining Markov analysis integrated with time dependent failures.

The conclusion drawn from this study was that the incremental reliability to incremental cost ratio for the main engine should always be greater than the original reliability to original cost ratio. Adopting this principle, would realise long term cost benefits (Anantharaman et al,2017).

By effectively altering the maintenance intervals of system components, the overall reliability of the system could be improved. A case study of turbocharger failure on a merchant vessel was studied and it was concluded that the turbocharger failure can have a major impact on the main engine operation, leading to immobilisation of the main engine. Hence matching of the turbocharger and main engine is extremely critical for safe and reliable operation of the main engine (Anantharaman, et al, 2018).

7.5 Impact of harsh working environment on the reliability of a main engine

The above paper aimed to look at the two main aspects, reliability and safety, on the operation of a bulk carrier in a harsh working environment. The reliability of the main engine ranging from 10% to 100% load was evaluated and a reliability compensating factor for the main engine system components in a harsh working environent was established. It was concluded that the impact of a harsh working environment per se, does not to a great extent impact on reliability (Mohan Anantharaman, et al, 2017).

7.6 Conclusions from data analysis

This study provides useful data for the reliability analysis of a main propulsion engine. The collected data is unique in this field of study. The large set of collected data enables generalization and processed data will help to develop reliability analysis techniques. The subjectivity and variability of the collected data are analysed and are found to be less than 10%. Therefore, it provides a higher confidence in the data and its generalization. The analysis of the data collected through a structural survey demonstrates significance of the main propulsion engines' subsystems and its components during the voyage. The collected relevant data from various sources are used to identify the most appropriate failure model representing specific components of a main propulsion engine. The results of this study indicate that not all the data for a component of a main propulsion engine's subsystem follow the same behaviour. Most of the components however were found to be following the exponential distribution. Therefore, it is concluded that time between failure models, which is exponential distribution, is the best fit for the collected data. This model will be very useful for a shipping company for planning their maintenance of the main propulsion engine. This provides the shipping companies a starting point from which to begin and to revise the model based on data from their own ships. Further work could consider Reliability assessment of the vessels main propulsion engine using Bayesian Network**.**

7.7. Further work

To evaluate reliability of the main engine the three major subsystems which include the lubricating oil, fuel oil and scavenge air system were considered. Further work could consider the cooling water system, the start air system and engine management system. It would be useful to study the impact of these systems on the reliability of the main engine. This should be considered in conjunction with the latest development of main engines which are electronically controlled. Whilst this research investigated large slow speed main propulsion engines, the research could be extended to medium speed and high-speed engines, which also form the propulsion driver for passenger ferries.

Furture studies need to look at other factors related to safety which should include cargo stowage, steering failure and failure of other auxiliary machinery, apart from the main engine failure. Further studies also need to take a holistic approach to reliability and safety, whilst operating the main engine in a harsh environment, This requires further analysis, evaluation and quantification of the safety factors to always ensure safe voyage.

The findings of this research should be made available in the form of a condensed book for engineers at sea serving on commercial vessels. Ship's engineers have very limited exposure to the knowledge of reliability engineering, due to the nature of their work schedule and working environment. The knowledge and study of reliability engineering related to ships engineering system should be transferred to seafarers. This knowledge will help a ship's engineer to understand and analyse a system more effectively and take appropriate action/s, to alleviate catastrophic failure of the ship's propulsion plant. This will alsso help to achieve high cost benefits to the maritime community.

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9. Appendix

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HUMAN RESEARCH ETHICS COMMITTEE (TASMANIA) NETWORK

UTAS

8 October 2014

Professor Faisal Khan
National Centre for Maritime Engineering and Hydrodynamics
Australian Maritime College
Locked Bag 1395

Student Researcher: Mohan Anantharaman

Sent via email

Dear Professor Khan

Re: MINIMAL RISK ETHICS APPLICATION APPROVAL
Ethics Ref: **H0014474 - Development of a Condition Based Maintenance (CBM) model for a vessels' main propulsion system**

We are pleased to advise that acting on a mandate from the Tasmania Social Sciences HREC, the Chair of the committee considered and approved the above project on 7 October 2014.

This approval constitutes ethical clearance by the Tasmania Social Sciences Human Research Ethics Committee. The decision and authority to commence the associated research may be dependent on factors beyond the remit of the ethics review process. For example, your research may need ethics clearance from other organisations or review by your research governance coordinator or Head of Department. It is your responsibility to find out if the approval of other bodies or authorities is required. It is recommended that the proposed research should not commence until you have satisfied these requirements.

Please note that this approval is for four years and is conditional upon receipt of an annual Progress Report. Ethics approval for this project will lapse if a Progress Report is not submitted.

The following conditions apply to this approval. Failure to abide by these conditions may result in suspension or discontinuation of approval.

1. It is the responsibility of the Chief Investigator to ensure that all investigators are aware of the terms of approval, to ensure the project is conducted as approved by the Ethics

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Committee, and to notify the Committee if any investigators are added to, or cease involvement with, the project.

2. Complaints: If any complaints are received or ethical issues arise during the course of the project, investigators should advise the Executive Officer of the Ethics Committee on 03 6226 7479 or human.ethics@utas.edu.au.

3. Incidents or adverse effects: Investigators should notify the Ethics Committee immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.

4. Amendments to Project: Modifications to the project must not proceed until approval is obtained from the Ethics Committee. Please submit an Amendment Form (available on our website) to notify the Ethics Committee of the proposed modifications.

5. Annual Report: Continued approval for this project is dependent on the submission of a Progress Report by the anniversary date of your approval. You will be sent a courtesy reminder closer to this date. **Failure to submit a Progress Report will mean that ethics approval for this project will lapse.**

6. Final Report: A Final Report and a copy of any published material arising from the project, either in full or abstract, must be provided at the end of the project.

Yours sincerely

Katherine Shaw
Executive Officer
Tasmania Social Sciences HREC